# TECHNICAL REPORT
# TR-NAVFAC-EXWC-EX-1601
# APRIL 2016

# REMOTE COLLABORATIVE 3D PRINTING - PROCESS INVESTIGATION



| AERIAL | VIRTUAL |
| CAD MODEL | PRINT MODEL |
| PRINT PREVIEW | PRINTED PART |
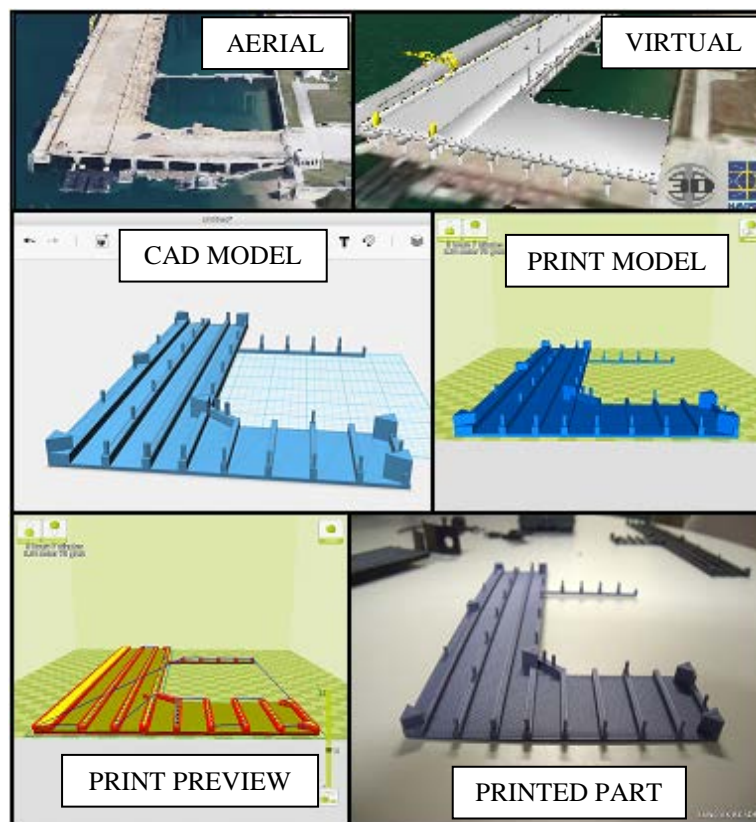
Cody M. Reese, PE

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The Remote Collaborative 3D Printing project is a collaboration between Strategic System Programs (SSP), the Naval Postgraduate School (NPS), NAVFAC Headquarters Asset Management - Facilities Integrated Product Support (IPS) Program, and the NAVFAC Engineering and Expeditionary Warfare Center (EXWC). The intent of the project was to investigate the end-to-end process of transferring, receiving, manipulating, and printing a digital 3D model into an additively manufactured component. Several digital models were exchanged, and the steps, barriers, workarounds, and results have been documented.

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# EXECUTIVE SUMMARY

The Remote Collaborative 3D Printing project is a collaboration between Strategic System Programs (SSP), the Naval Postgraduate School (NPS), NAVFAC Headquarters Asset Management - Facilities Integrated Product Support (IPS) Program, and NAVFAC Engineering and Expeditionary Warfare Center (EXWC). The intent of the project was to investigate the end-to-end process of transferring, receiving, manipulating, and printing a digital model into an additively manufactured component. Several digital models were exchanged, and the steps, barriers, workarounds, and results have been documented. As a process investigation, limited analysis was conducted on the actual quality of produced parts, however basic observations on printer settings, power consumption, economics, and material performance were made and documented. In addition to the original models sent for evaluation, several models sourced from online model exchanges and libraries were printed, and process and product lessons-learned were documented.

EXWC has productively employed 3D printers in concept visualization and limited production prototyping for destructive testing applications. In 2015, EXWC printed over $50k worth of plastic, avoiding over $500k of traditional prototype fabrication costs. EXWC used two 3D printers for this investigation; a Stratasys Dimension SST 1200es, and a Lulzbot TAZ5. The Stratasys Dimension 1200es is an entry-level commercial-grade Fused Deposition Model (FDM) printer, costing approximately $35,000, and the Lulzbot TAZ5 is a high-end consumer-grade FDM desktop printer costing approximately $2,000. The TAZ5 was used predominantly for this investigation due to the significantly lower operating cost compared to the 1200es.

EXWC attempted to take various model files through the process to execute physical prints for models of facilities, equipment, and parts. None of the original files for consideration were able to be completely processed end-to-end from an NMCI computer, due to the lack of available slicing software and limitations on connecting NMCI assets to the 3D printer hardware at EXWC. However, using non-NMCI computing assets, a pier model, SSBN fire extinguisher bracket model, and rope cleat model were successfully printed. The Ohio-replacement submarine was not able be processed for printing with the available tools and software on-hand, however a publicly sourced model of an Ohio class submarine was able to be printed.

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# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ABS | Acrylonitrile Butadiene Styrene |
| AM | Additive Manufacturing |
| AMRDEC SAFE | Aviation and Missile Research Development and Engineering Center - Safe Access File Exchange system |
| CAD | Computer Aided Design |
| DMLM | Direct Metal Laser Melting |
| DMLS | Direct Metal Laser Sintering |
| ePLM IDE | Enterprise Product Lifecycle Management - Integrated Data Environment |
| FDM | Fused Deposition Modeling |
| HIPS | High Impact Polystyrene |
| INLS | Improved Navy Lighterage Systems |
| IPS | Integrated Product Support |
| NAVFAC EXWC | Naval Facilities Engineering Command - Engineering and Expeditionary Warfare Center |
| NIH | National Institute of Health |
| NMCI | Navy Marine Corps Internet |
| NOTU | Naval Ordinance Test Unit |
| NPS | Naval Postgraduate School |
| PLA | Polylactic Acid |
| RC3DP | Remote Collaborative 3D Printing |
| SLA | Stereolithography |
| SLS | Selective Laser Sintering |
| SSP | Strategic Systems Programs |
| SST | Soluble Support Technology |
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## 1.1. Project concept:

The Remote Collaborative 3D Printing project is a collaboration between Strategic Systems Programs (SSP), the Naval Postgraduate School (NPS), NAVFAC Headquarters Asset Management Facilities Integrated Product Support (IPS) Program, and the NAVFAC Engineering and Expeditionary Warfare Center (EXWC). The intent of the project was to investigate the end-to-end process of transferring, receiving, manipulating, and printing a digital model into an additively manufactured component. Several digital 3D models were exchanged, and the steps, barriers, workarounds, and results have been documented.

## 1.2. Introduction to 3D printing:

3D printing is a type of Additive Manufacturing (AM) process. Many familiar manufacturing processes are subtractive, where the end part is comprised of less material than is started with. For example, machined parts are cut out of a block of material that is larger than the desired finished part.  3D printing is an additive net-shape process, whereby material is added bit by bit to build up a final component. There are many types of 3D printers that work via different mechanics, including: Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Binder Jetting, Stereolithography (SLA), and Direct Metal Laser Sintering/Melting (DMLS/DMLM), which employ different materials (plastics, paper, metal, fiber-reinforced composites, ceramics, ice, foods, biological materials, etc.). In all cases, the concept is the same - a part is built up bit by bit, layer by layer, into a final shape.

There are several uses for 3D printing. Some low-volume, high-complexity components are printed directly for end-use applications. However, at this point in time, most 3D printers are used to create representational models or form-studies for evaluation and prototyping purposes. These types of 3D printed prototypes are valuable engineering tools, which can be produced at a significant cost savings compared to traditional production methods. These prototype parts are used for pre-visualization and concept evaluation, fitment and assembly checks of both miniature and full-scale parts, and complex visual evaluation and component interaction studies.

EXWC currently operates three 3D printers, including a two Fused Deposition Model type and a powder-bed Binder Jet (3D Inkjet) type. They have been productively employed in concept visualization prototyping, form-studies, and limited production prototyping for destructive testing applications. In 2015, EXWC printed over $50k worth of plastic, avoiding over $500k of traditional prototype fabrication costs.

## 2. DIGITAL FILE INVESTIGATIONS:

Over thirty different 3D model files of various formats were manipulated and printed as part of this investigation, including eight files transferred from NAVFAC Headquarters, and several models obtained from various free online model libraries.

### 2.1. Files from NAVFAC HQ and NPS:

The following files were transferred to EXWC via email and/or the US Army Aviation and Missile Research Development and Engineering Center - Safe Access File Exchange system (AMRDEC SAFE), depending on file size.

- NOTU_TRIDENT_WHARF_OR-NEW_NORTH_FT_20150401.dwg (AutoCAD model of a pier with docked submarines)
- NOTU_TRIDENT_WHARF_OR-NEW_SOUTH_FT_20150401.dwg (AutoCAD model of a pier with docked submarines)
- OR_FULL_M_20150612.dwg (AutoCAD model of the Ohio Replacement Submarine hull)
- WholeBoat10032013-3D.stp (Step file model of the Ohio Replacement Submarine)
- OBJECT_OHIO_REPLACEMENT_M_20150624.wrl (WRL model of the Ohio Replacement Submarine)
- R8611505-96_B.jt (Siemens NX model of a fire extinguisher bracket)
- R8611505-96_B.stl (STL model of a fire extinguisher bracket)
- R8611505-96_B.stp (Step file model of a fire extinguisher bracket)
- Cleat Test.x3d (.x3d model of a rope cleat developed by NPS)

### 2.2. Model Libraries

The following model libraries were browsed, and select files were downloaded and printed from each source.

- McMaster Carr: http://www.mcmaster.com
- Thingiverse: http://www.thingiverse.com
- NIH 3D print exchange: http://3dprint.nih.gov
- NPS Savage .x3d model library https://savage.nps.edu/Savage/
- Sketchup 3D Warehouse https://3dwarehouse.sketchup.com/?hl=en

### 2.3. Files printed from Model Libraries and other sources

- Vanderbilt mansion section (Lulzbot sample file)
- Rocktopus (Lulzbot sample file)
- Pipe end-cap (Step file model from McMaster.com)
- I-400 class Japanese submarine (.skp model from Sketchup 3D warehouse)
- LPD-17 (.x3d model from savage.NPS.edu)
- Custom shadowbox model (Modeled in Autodesk 123D Design)

# 3. SOFTWARE, TOOLS, AND EQUIPMENT

As a free-form investigation of process, involving both software and hardware, this project engaged the use of many different software and hardware tools. The following were used throughout the course of this project:

### 3.1. Software utilized on NMCI assets

- AutoCAD 2010 (Autodesk)
- Inventor 2014 (Autodesk)
- Solidworks 2014 (Dassault Systems)
- AMRDEC SAFE: https://safe.amrdec.army.mil/safe/
- SPIDERS 3D (NAVFAC): https://www.navfac.navy.mil/products_and_services/am/products_and_services/Integrated_Product_Support/spiders_3d.html

### 3.2. Software utilized on non-NMCI assets

- Cura - Lulzbot edition (free / open source, v15.02.1-1.03)
- AutoDesk 123D Design (free)
- Sketchup Pro 2015 and 2016 (trial version)
- Autodesk Meshmixer (free, v10.10.170)
- Autodesk Print Studio (free, Technical Preview, v1.5)
- Stratasys Catalyst (v4.3)
- Blender (free, v2.76b-OSX_10.6-x86_64)
- Slic3r (free, v1.2.9)

### 3.3. Tools and equipment:

- Clam Knife (dull knife used for part removal)
- Metal spatula (sharpened tip, used for part removal)
- Various small knives (used for part deburring)
- Chisel (used for part deburring)
- Small scissors (used for part deburring)
- Oven (for annealing warped parts)
- Baking pan (used for annealing)
- Clean sand (used for annealing)
- Bricks (used as weights in the annealing process)

### 3.4. 3D Printers:

Two 3D printers were used in the course of this investigation; a Stratasys Dimension SST 1200es, and a Lulzbot TAZ5. The Stratasys Dimension 1200es is an entry-level commercial-grade

FDM printer, costing approximately $35,000, which EXWC has operated since approximately 2012. The 1200es has a dual print head, and prints both a primary and a support material, allowing for very complex geometries to be produced. Proprietary "ABS*plus*" filaments are required. The system has been used extensively to prototype parts for various EXWC projects. The printer is driven directly by the Stratasys Catalyst 4.3 software package running on a non-NMCI laptop.

The Lulzbot TAZ5 is a high-end consumer-grade FDM desktop printer. The system was purchased in 2015, and cost approximately $2,000 as equipped with a single print head (though the machine is multi-head capable). Equipped with a single print head, the machine is still capable of generating support material that is designed to snap-off after the print is complete, similar to a plastic hobby-model kit. A wide variety of non-proprietary bulk filaments are available for this machine, and EXWC has printed PolyLactic Acid (PLA), High Impact Polystyrene (HIPS), Acrylonitrile Butadiene Styrene (ABS), and Nylon. The printer is driven by g-code files, generated by any number of slicing engines, such as Cura, Autodesk Print Studio, Slic3r, and others. The printer can be driven via direct control to a computer, or the g-code files can be loaded onto an SD card and run from a small control interface on the printer itself. The TAZ5 was used predominantly for this investigation due to the significantly lower operating cost compared to the 1200es, which is based on the lower price and availability of materials for the TAZ5, the consumable build-platform of the 1200es, and higher energy consumption on the 1200es due to the enclosed heated build volume.

## 4. WORKFLOW
The typical workflow associated with a 3D print operation using an FDM machine is as follows.

1. *Obtain model:* This is accomplished through direct electronic file transfer, download from a model library, 3D scanning, or local model creation via a CAD package or other software tool.
2. *Manipulate model:* This is performed in CAD, graphics, or slicing software on an as-needed basis to convert file format, validate model integrity, and/or repair model errors. Typically, a model must be converted, repaired, and validated as a fully enclosed solid, which contains no open holes in a surface mesh. Any "holes" in a model may result in part or all of the model rendering as a thin shell instead of a solid object.
3. *Establish print parameters:* Once a model has been validated, prepared for printing, and formatted, the parameters of the print job must be set up. This includes customizing settings like model orientation, layer thickness, fill percentage, shell thickness, print material, nozzle and bed temperatures, support type, etc. Typical 3D printing software packages (slicers) have a basic mode with controls for position and scaling, and simple selections for material, quality (e.g. fast, normal, or fine), as well as an advanced mode with extensive control over a wide array of individual machine parameters (e.g. travel speed, support type, filament retraction, overhang angle threshold, etc.) A model loaded into Cura slicing software is shown in figure 1.

4. *Preview print operation:* Once the print parameters have been set, a tool path is generated in the slicing engine, and a layer-by-layer preview of the print operation is presented, as shown in figure 2. This preview is reviewed for any irregularities that may lead to print failure, such as missing layers, strange tool path movements, or unsupported overhangs.

5. *Generate print-file:* Once the print preview has been reviewed and validated, the tool path file is saved.

6. *Establish printer connection:* When ready to print, the computer is either connected directly to the printer, or the print file is saved to removable media (e.g. SD card) and loaded into the printer.

7. *Configure printer:* The printer is turned on, calibrated if needed, loaded with appropriate material, and warmed up.

8. *Execute print:* The print is initiated, and monitored as needed, as shown in figure 3.

9. *Recover printed objects:* Once the print is completed, the resulting objects are removed from the printer and the printer is shut down.

10. *Post-process printed object:* Once recovered from the printer, an object may require post processing. This can include trimming of flash, removal of support material by trimming or dissolving in a chemical bath, sanding, painting, or otherwise prepping for appearance, or post-machining any high-tolerance features.
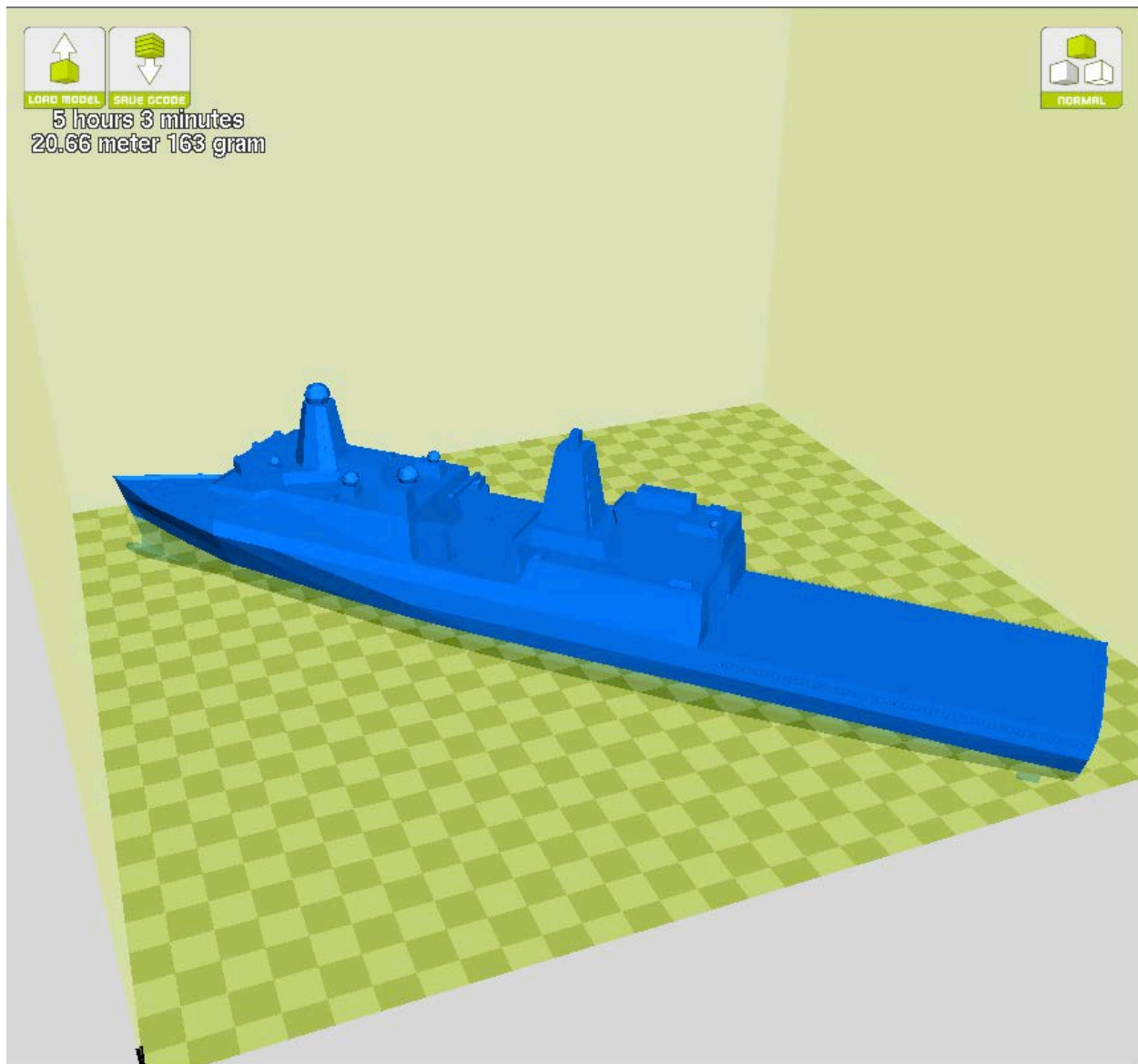
**Figure 1: This LPD17 model was sourced from savage.nps.edu, converted from .x3d to .stl using Blender, and loaded into Cura slicing software.**
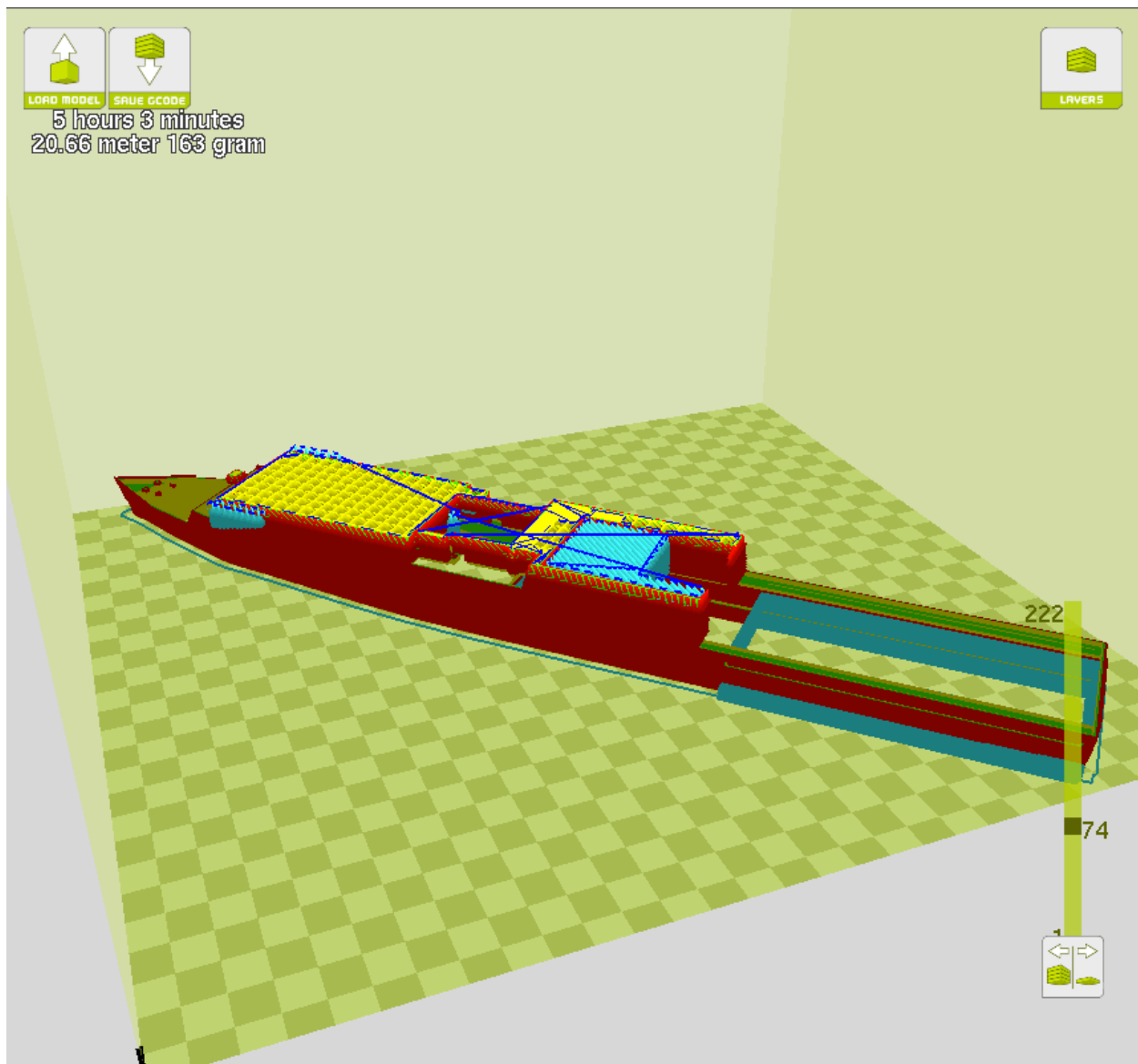
**Figure 2: Slicing software such as Cura is able to display a layer-by-layer build preview. Here, red represents shell material, yellow represents infill, light blue represents support, and dark blue represents nozzle-movement.**
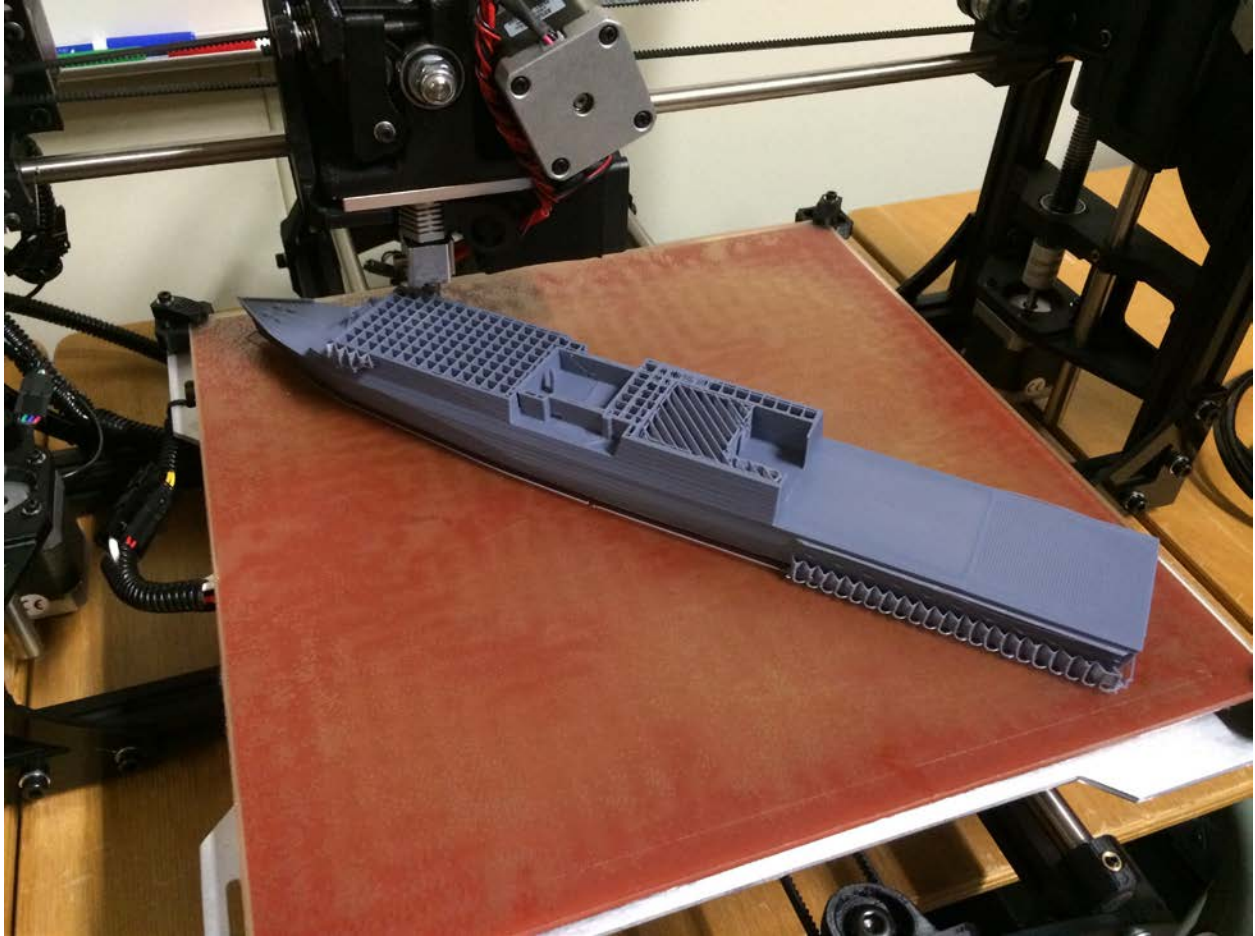
**Figure 3: The execution of the print job exactly matches the build preview as displayed in Cura.**

## 5. RESULTS FOR SPECIFIC FILES

### 5.1. Pier

Files:

- NOTU_TRIDENT_WHARF_OR-NEW_NORTH_FT_20150401.dwg
- NOTU_TRIDENT_WHARF_OR-NEW_SOUTH_FT_20150401.dwg

Progress:

EXWC was able to open these files on an NMCI computer with AutoCAD 2010.  The file opened as a 2D plan view of the pier outline in gray, with two colorfully detailed subs docked alongside. Turning on all layers and clicking through several objects indicated that they were classified as 3D objects, revealing the reason for the large 176MB file size.  Initiating the "orbit" command in

AutoCAD revealed this to be a 3D model. AutoCAD 2010 appears to have the ability to export as a .stl file, however attempts to export portions of the file resulted in an error.  EXWC was also able to open this file with Autodesk Inventor 2014, however the software recognized the file as a .dwg and presented a significantly reduced toolset with which to manipulate the model.

Working with AutoCAD 2010, we were able to isolate the sub and the pier into separate files by saving multiple copies of the drawing and deleting the unwanted elements from each. The pier was divided into three sections to enable printing of the facility at a relevant scale, from within the constrained print volume of the 3D printers. Interlocking features were designed into each section to facilitate connection and alignment on reassembly. Deck features were stripped, the pilings were cut at the waterline (as shown in figure 4), and support features (i.e. feet) were added to improve the stability and robustness of the model. After manipulation of the models in AutoCAD, the files were saved as .stl files, burned to a CD, and loaded into Cura (a slicing and g-code engine) on a non-NMCI computer. Cura was utilized to adjust print parameters, preview jobs, and output g-code to drive the printers. To print on the TAZ5, the g-code was transferred to an SD card, which was inserted into the TAZ5 printer, and models were printed directly from the card using the printer control panel. Several print jobs were executed, in various materials, at various scales, and lessons learned from each iteration were documented.
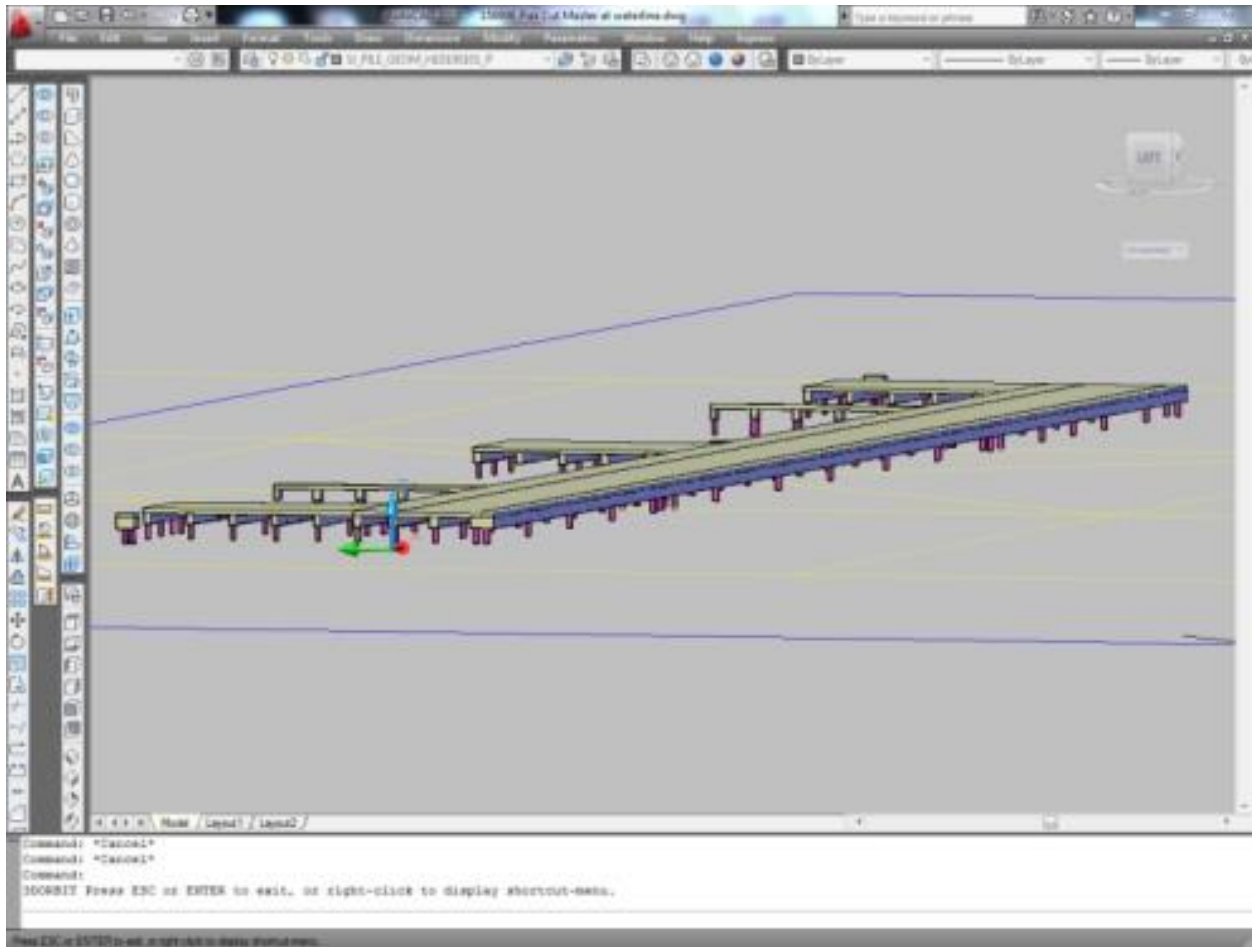
**Figure 4: The NOTU pier was prepared for printing by removing fine detail and superfluous components.**

*Pier Print 1 (TAZ5-0002):* At the desired desktop scale, all surface features on the pier exceed the print resolution of our printers. The pier deck was stripped down to a near-flat surface by cycling through all drawing layers and removing all extraneous components and features. On the underside of the pier, all pilings were cut at the water-line, and most pilings were removed to increase print speed. For all removed pilings, a socket-like hole was left in place of the piling such that small dowels could be inserted to represent pilings if necessary. This print was executed on the TAZ5 printer in Polylactic Acid (PLA). On this first attempt, a small curb was left around the perimeter of the deck. This geometry resulted in the need for a support layer to be printed under the majority of the deck, which led to difficult post processing and a poor resultant surface finish as shown in figures 7 and 8. The bottom of the part required extensive deburring due to tiny fibers of material left during nozzle transition over an unsupported surface (also known as manufacturing flash, shown in figure 5). This was most apparent on the pilings. Additionally, the printer was unable to resolve the edges of the sockets left in the positions from which we had removed pilings as shown in figure 6. Though a Fused Deposition Model printer may have high accuracy in the XY plane, the resolution of some features (e.g. narrow edges) is determined by the extrusion diameter. In this material, and at this scale, the pilings are extremely fragile, and easily broken off in spite of careful handling.
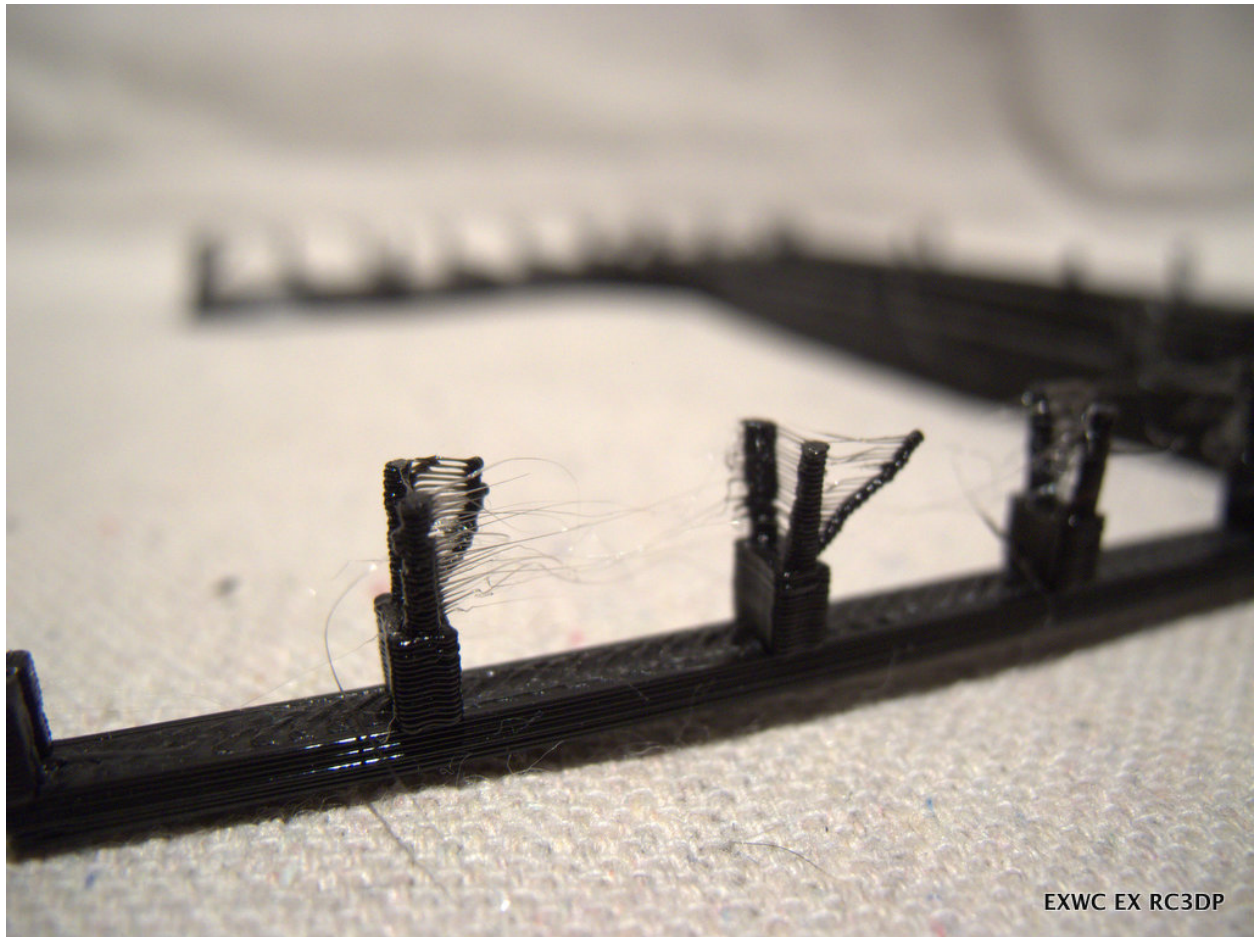
**Figure 5: The first print of a NOTU pier section in PLA plastic exhibited extensive flash and filament trails coming from the pilings.**
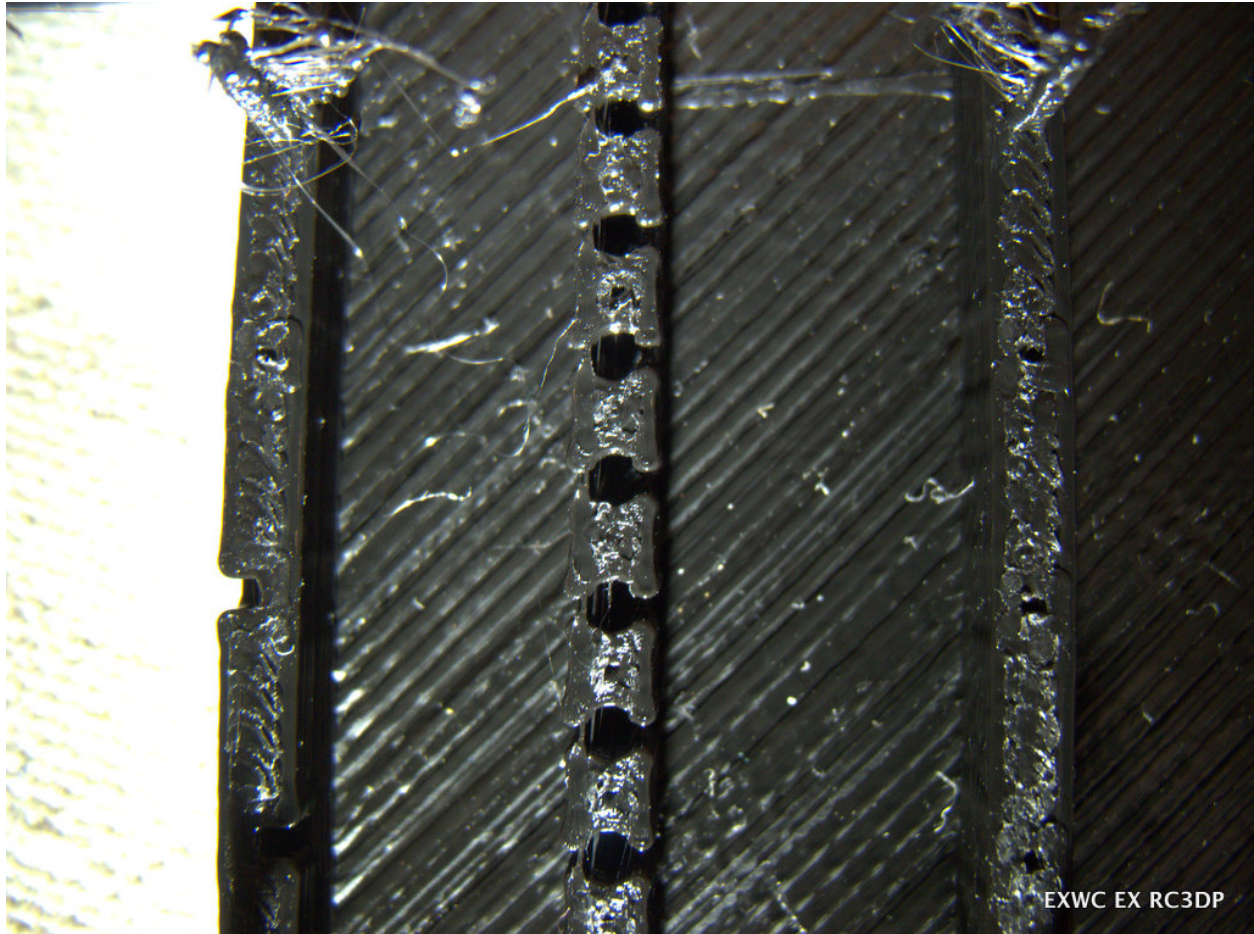
**Figure 6: This underside close-up of the first pier print illustrates the inability of an FDM printer to resolve features smaller than the diameter of the extruded filament**

**Figure 7: The first printed pier section required extensive deburring due to the support layer printed beneath the entire part.**

**Figure 8: Various tools were used to facilitate the deburring operation, and the rough surface finish of the pier deck can be seen where the support layer was removed.**

*Pier Print 2 (TAZ5-0003):* After the initial attempt, all surface features were eliminated to provide a perfectly flat base layer, all piling sockets were eliminated, and large triangular support features were added to the bottom of the pier to protect the pilings and enhance stability. The flat build surface and elimination of the piling sockets significantly reduced the build time and improved quality. The print parameters were also adjusted to reduce the shell thickness of the part. The single layer of the shell thickness can be observed in figure 9. The resultant print still required extensive deburring of the flash leftover on the pilings.

EXWC EX RC3DP
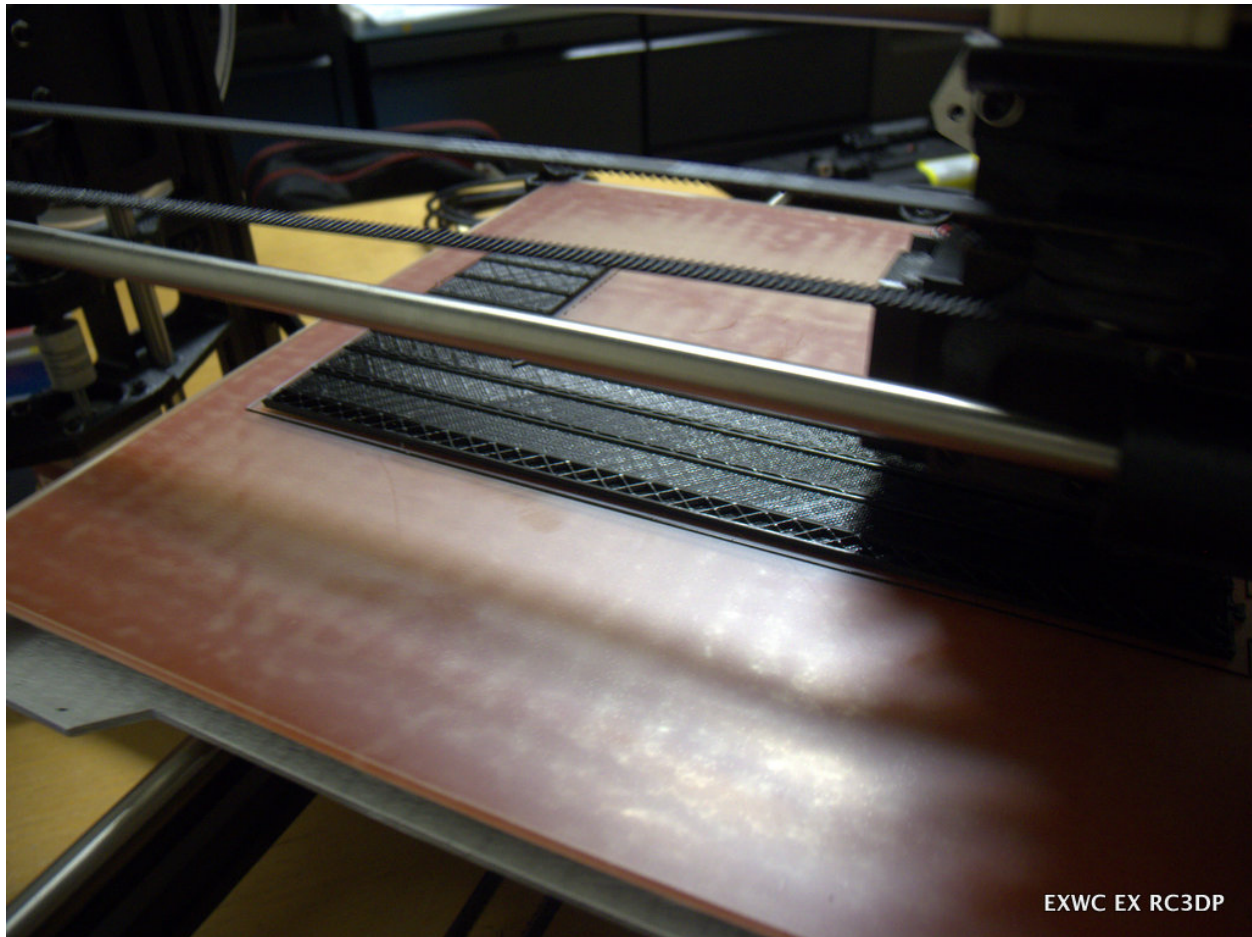
**Figure 9: The second print of the NOTU pier with revised parameters shows the thinness of the top layer covering crosshatched infill material.**

*Pier Print 3 (TAZ5-0004):* After the first two attempts, it was realized that the first two pier sections had been printed too large (0.75x scale from the .stl file) to accommodate the longest remaining section (the center section of the pier) within the build volume. The center section of the pier was loaded and scaled to the maximum X-dimension of the build volume (0.51x scale). Due to the smaller scale of the print, the print was generated as a solid body (no fractional infill). Several minutes into the first print layer, the incoming PLA-feed to the print head snapped, resulting in print failure as shown in figure 10.
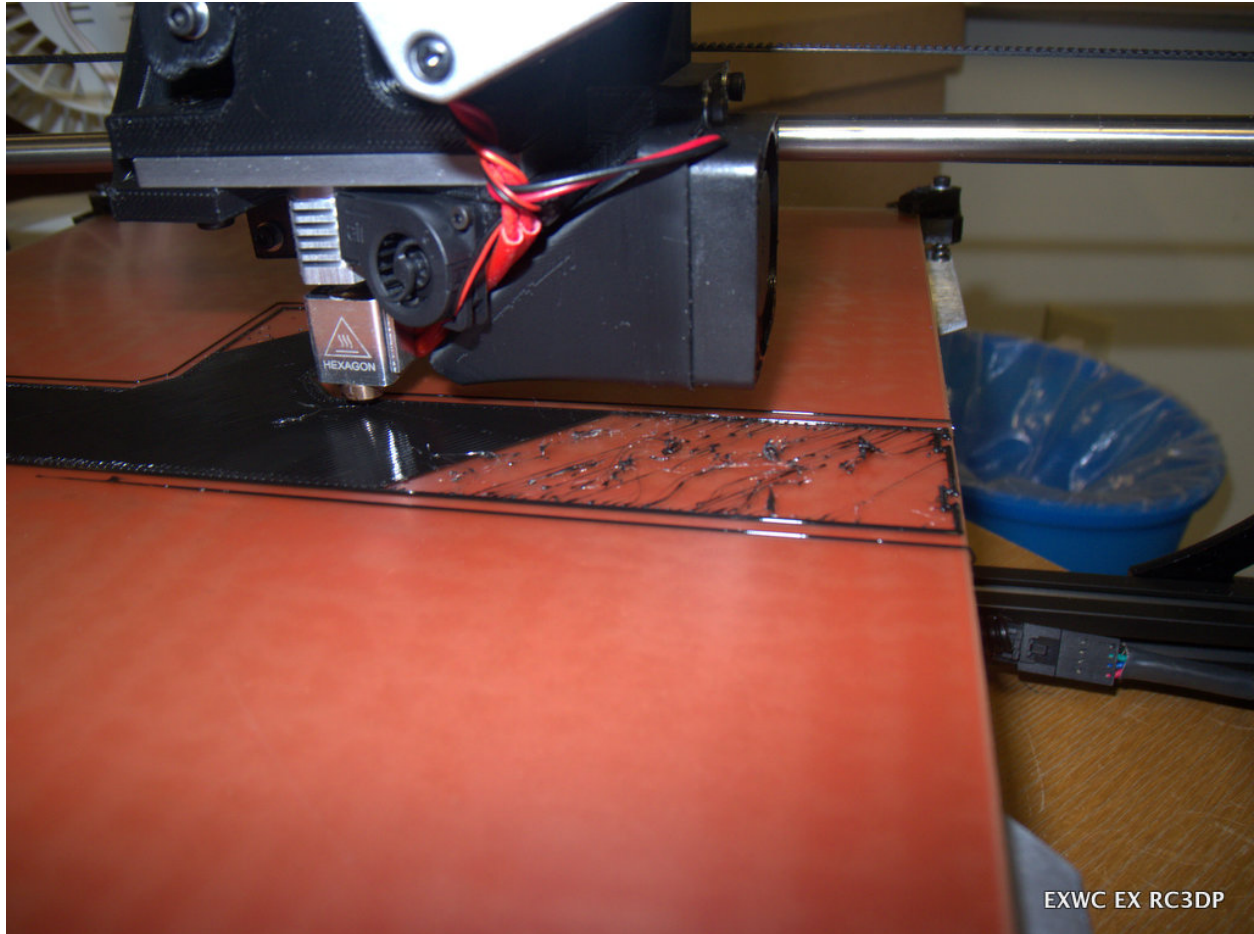
**Figure 10: This print failed due to a broken filament feed into the print head.**

*Pier Print 4 (TAZ5-0005):* The PLS feedstock was reloaded, and the print job of the center section was successfully executed as shown in figure 11. As with the earlier PLA models, the part required extensive deburring of flash from the pilings.
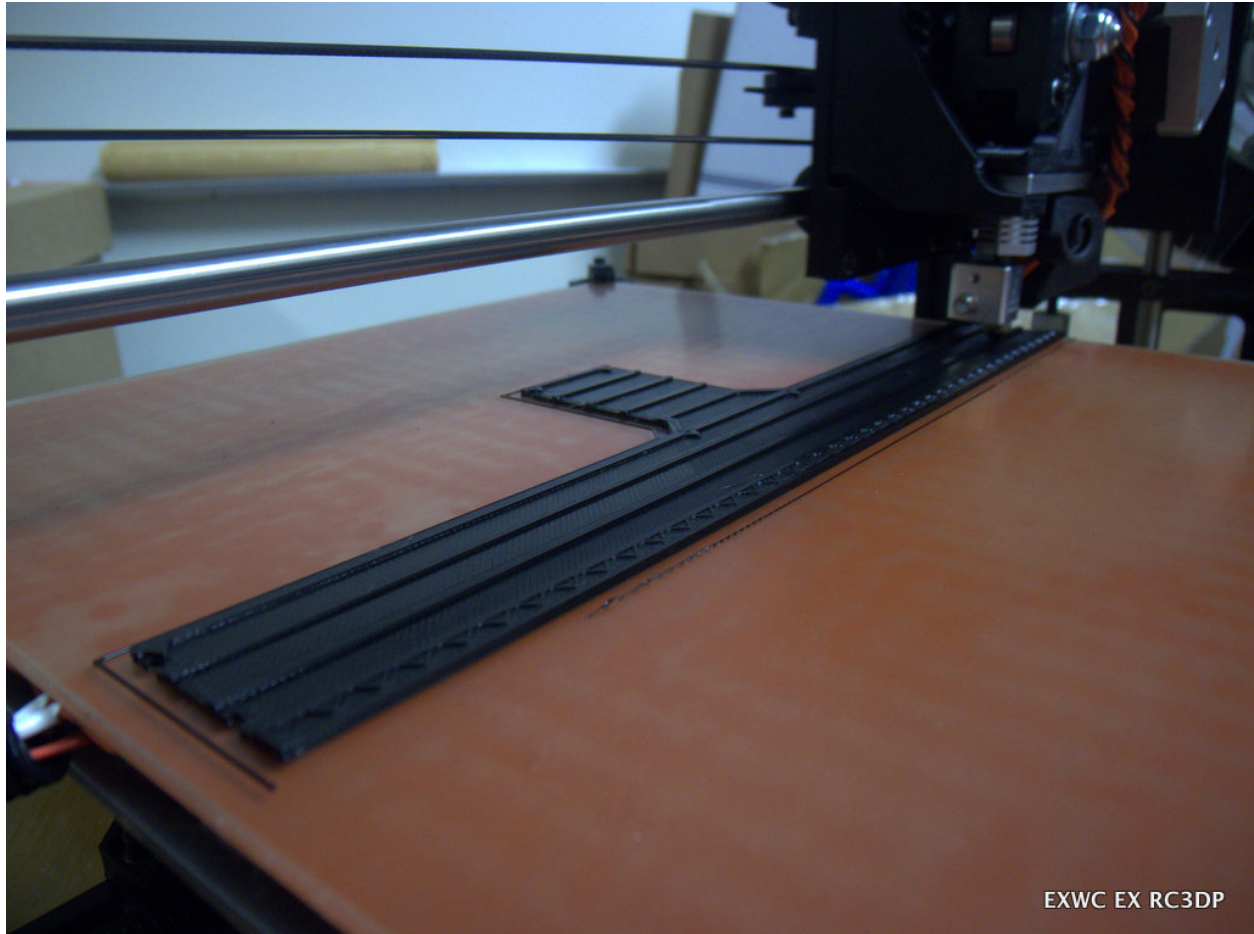
**Figure 11: The NOTU pier center section was printed at the maximum available print area of the machine.**

*Pier Print 5 (TAZ5-0006):* The first pier end section was successfully printed at the 0.51x scale to match the center section. Extensive deburring was required, and the pieces were able to be joined together as shown in figure 12.
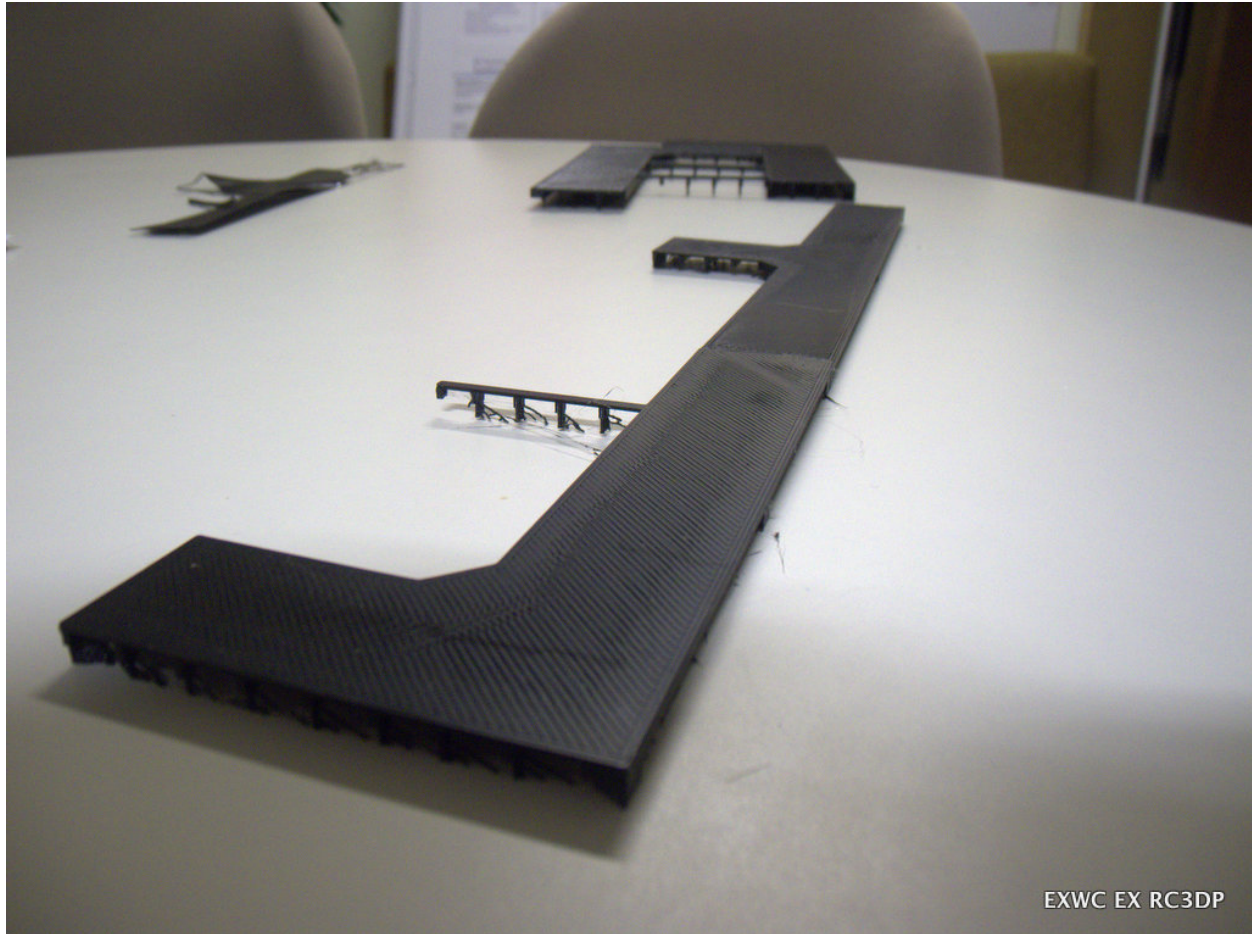
**Figure 12: The pier sections were able to be joined together after deburring and interlocking connector finishing operations.**

*Pier Print 6 (TAZ5-0007):* The second end section was successfully printed at the 0.51x scale. Extensive deburring was required. Attempts to connect the pier sections together with the interlocking features were frustrated due to the printed accuracy of the interlocking features. The features were manually filed down in order to interlock properly and secure the pier as a single unit.

*Pier Print 7 (TAZ5-0010):* Immediately rior to this print, the print material in the TAZ5 was switched to High Impact Polystyrene (HIPS). It was realized that we could maximize the printed size of the pier by printing the center section at a 45 degree angle on the square build plate. Arranging the center section as such revealed that printing at a 0.60x scale was possible. One pier end was printed at the 0.60x scale, as a solid part, from HIPS. The print exhibited dimensional overruns (i.e. bumps) at corners and other directional changes (as shown in figure 13) required additional processing and finishing in order to mate properly. The resultant finish quality from using HIPS was superior to the earlier PLA parts as shown in figure 14. HIPS parts exhibited none of the flash observed on the PLA parts are require no deburring, as shown in

figure 15. However HIPS requires a higher extrusion temperature (240 C), and higher bed temperature (110 C) to achieve adhesion. HIPS also exhibits more thermal expansion than PLA. Due to the heated bed, the pier surface was maintained at 110 C while the underside of the pier (the top layers when printed upside down) was exposed to air and cooled in real-time during the course of the print job. On job completion and removal from the build plate, the pier surface cooled and contracted, resulting in a significant warping of the part as shown in figure 16.
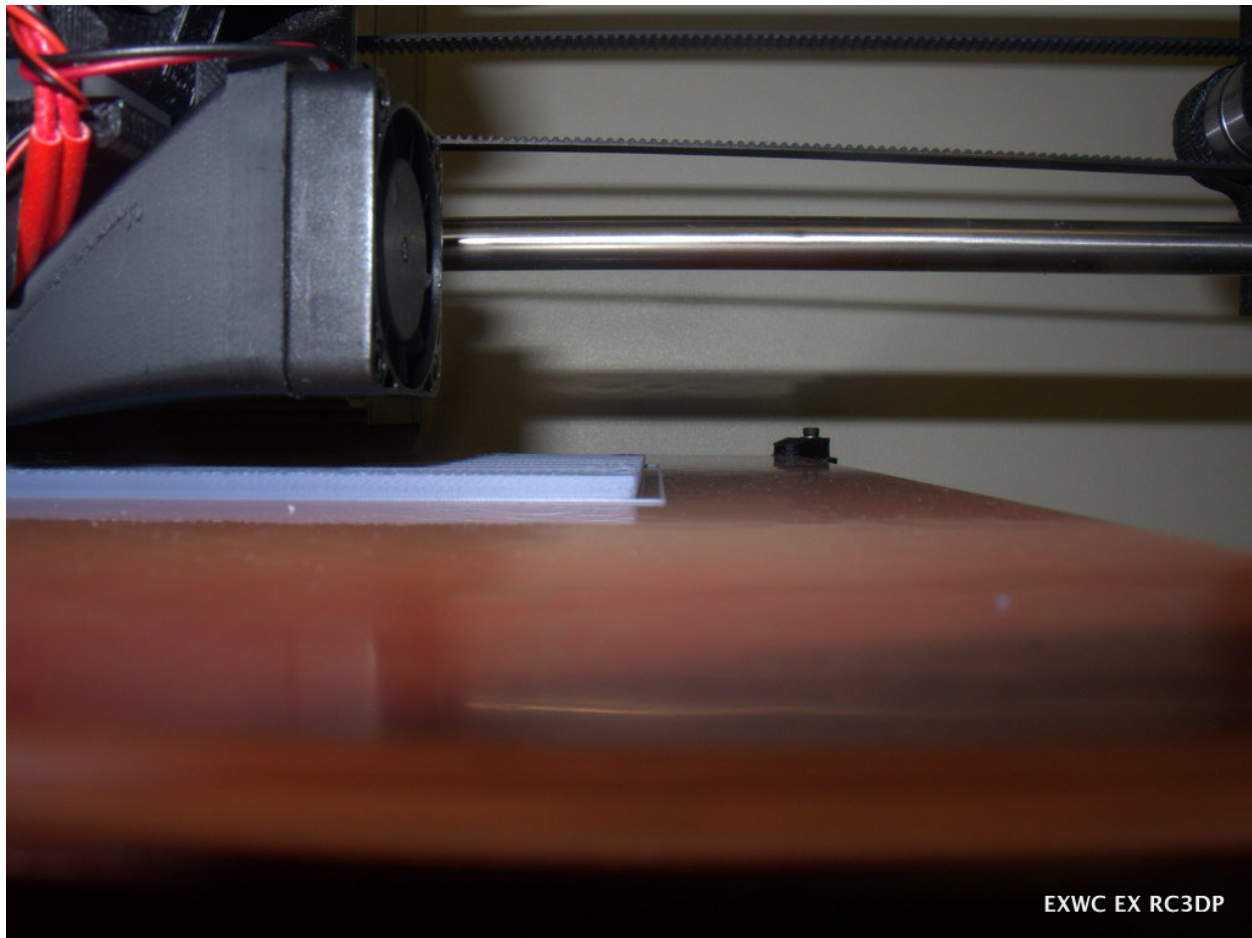


**Figure 13: The pier section printed in HIPS showed geometric distortion on what should have been a vertical surface.**
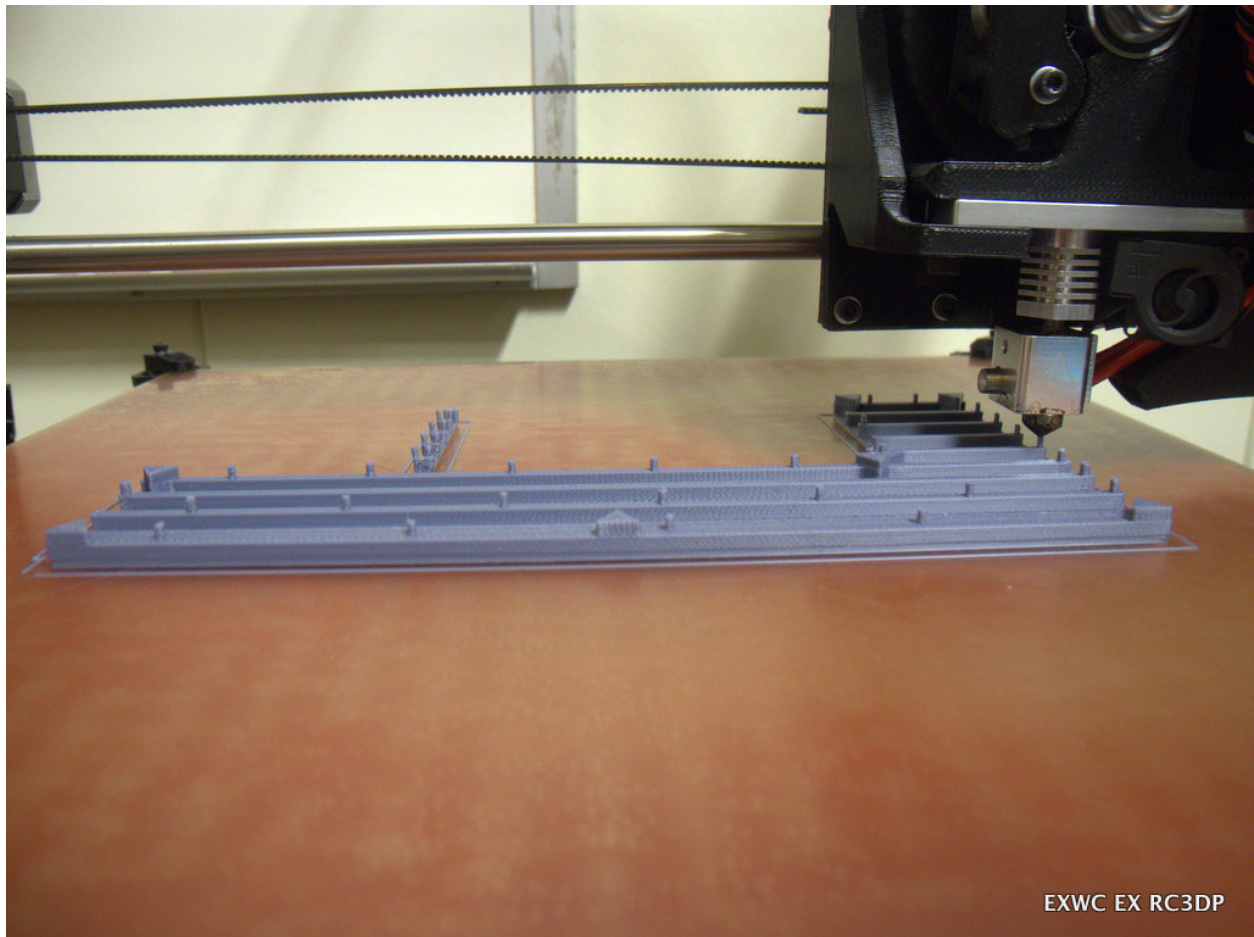
**Figure 14: This pier section was printed using HIPS material as a completely solid part.**
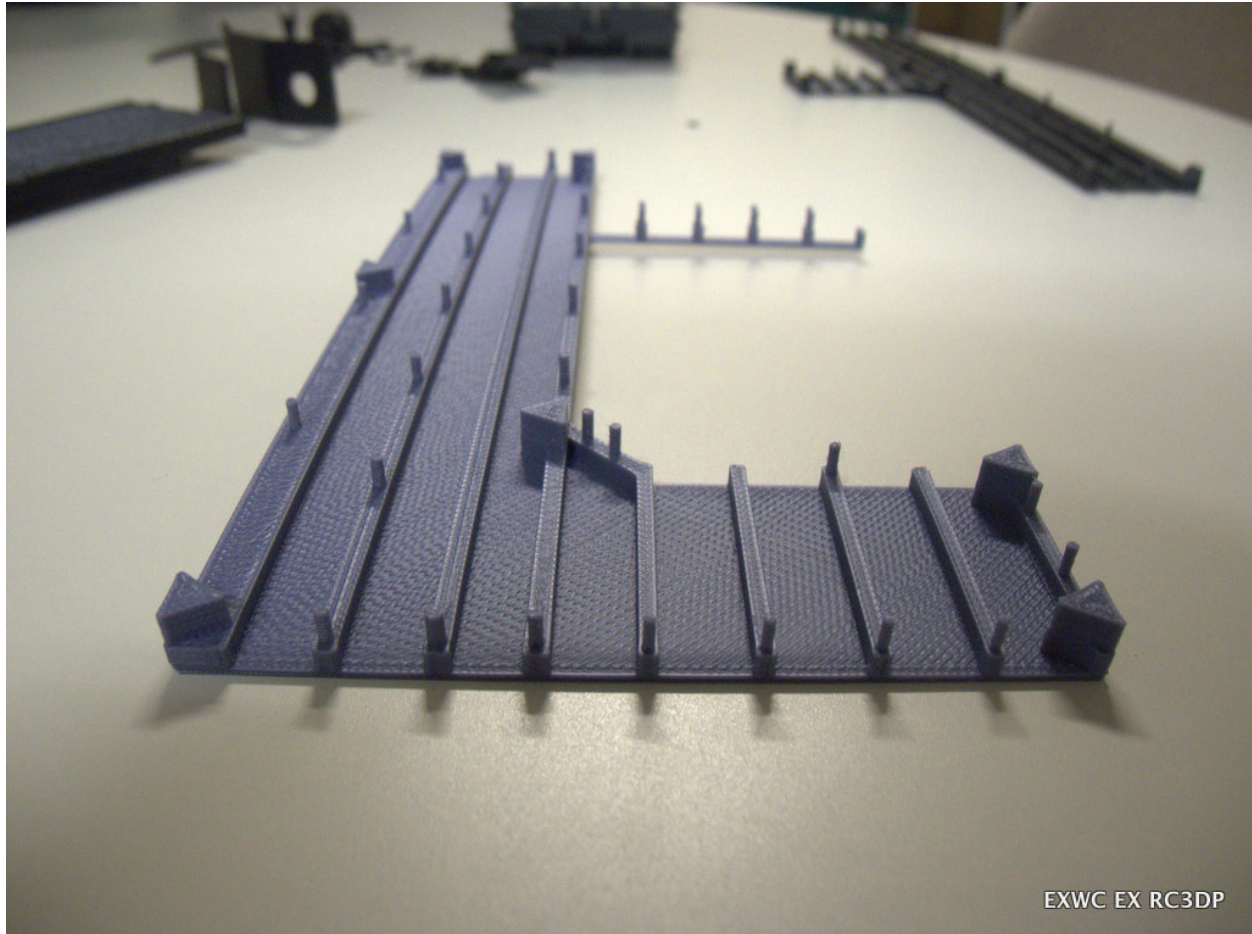
**Figure 15: The pier section printed in HIPS is shown as-removed from the machine, exhibiting high finish quality with no deburring required.**
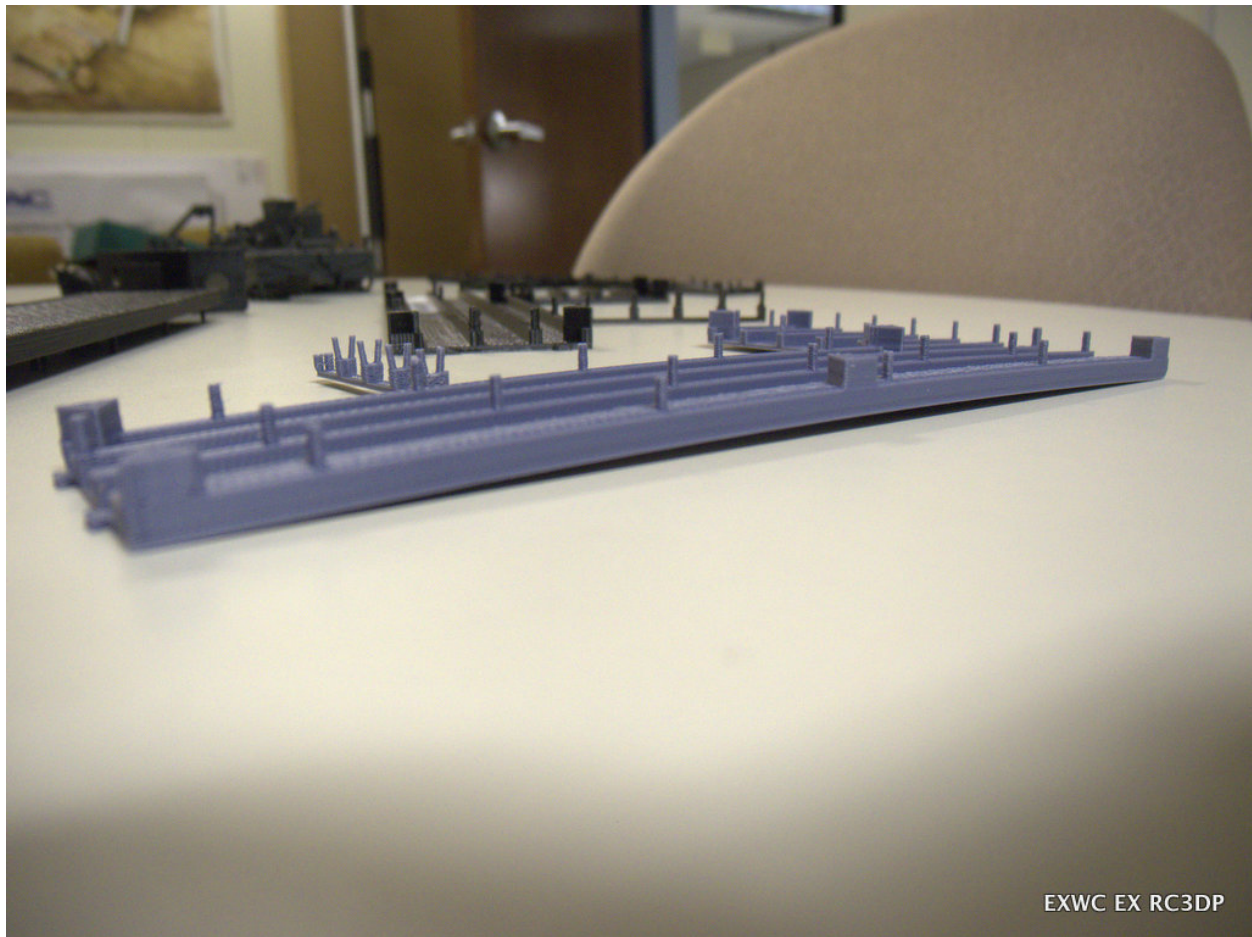
**Figure 16: HIPS parts exhibit significant warping due to residual thermal stress from the heated build-plate, causing an uneven temperature profile through the thickness of the part.**

*Pier Print 8 (TAZ5-0011):* The second pier end section was printed at 0.60x scale as a solid HIPS part. As with the first, this part exhibited outstanding quality with no deburring required, however it suffered from the same warping phenomenon caused by residual thermal stress.

*Pier Print 9 (TAZ5-0012):* The center section of the pier was printed at 0.60x scale, arranged at a 45 degree angle on the build plate, as a solid HIPS part as seen in figure 17. As with the other HIPS pier prints, this part exhibited outstanding quality with no deburring required, however suffered from the same warping phenomenon as seen in figure 18. The warping impaired the ability of the models to mate properly with the interlocking features as shown in figure 19.
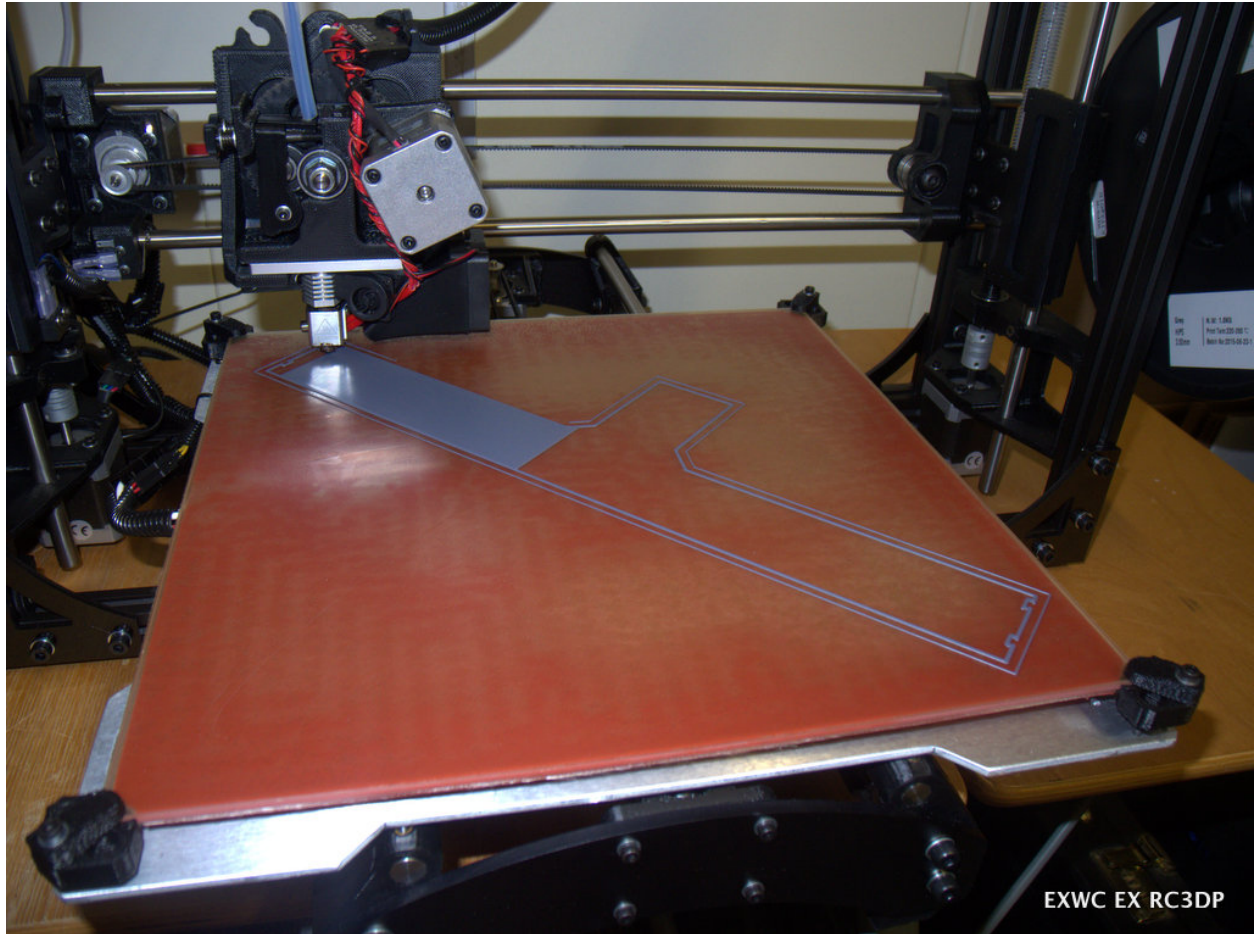
**Figure 17: The center section of the pier was printed at a 45-degree angle to maximize the available print area.**
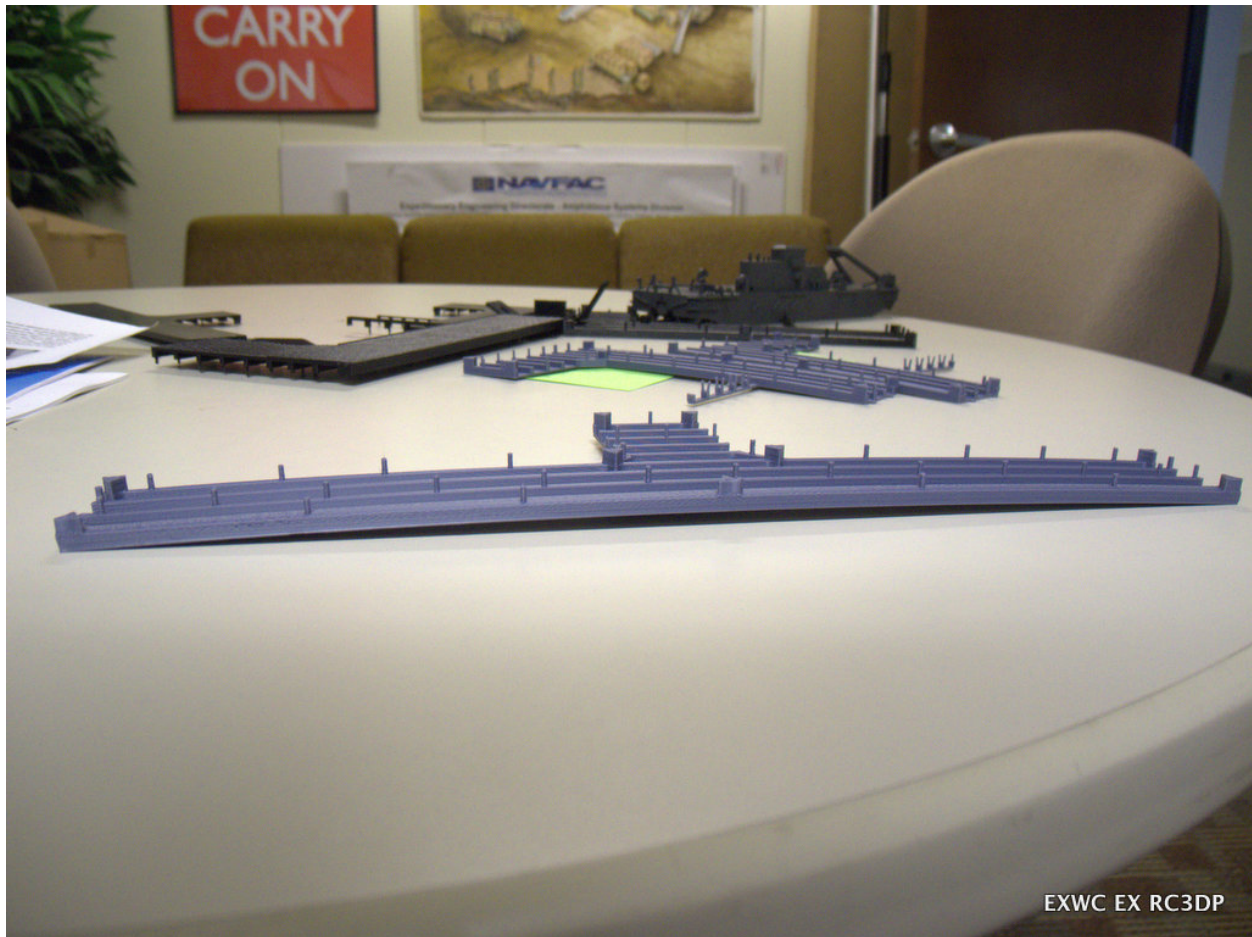
**Figure 18: Extreme warping caused by residual thermal stress can be seen in the long, center section of the pier.**

EXWC EX RC3DP
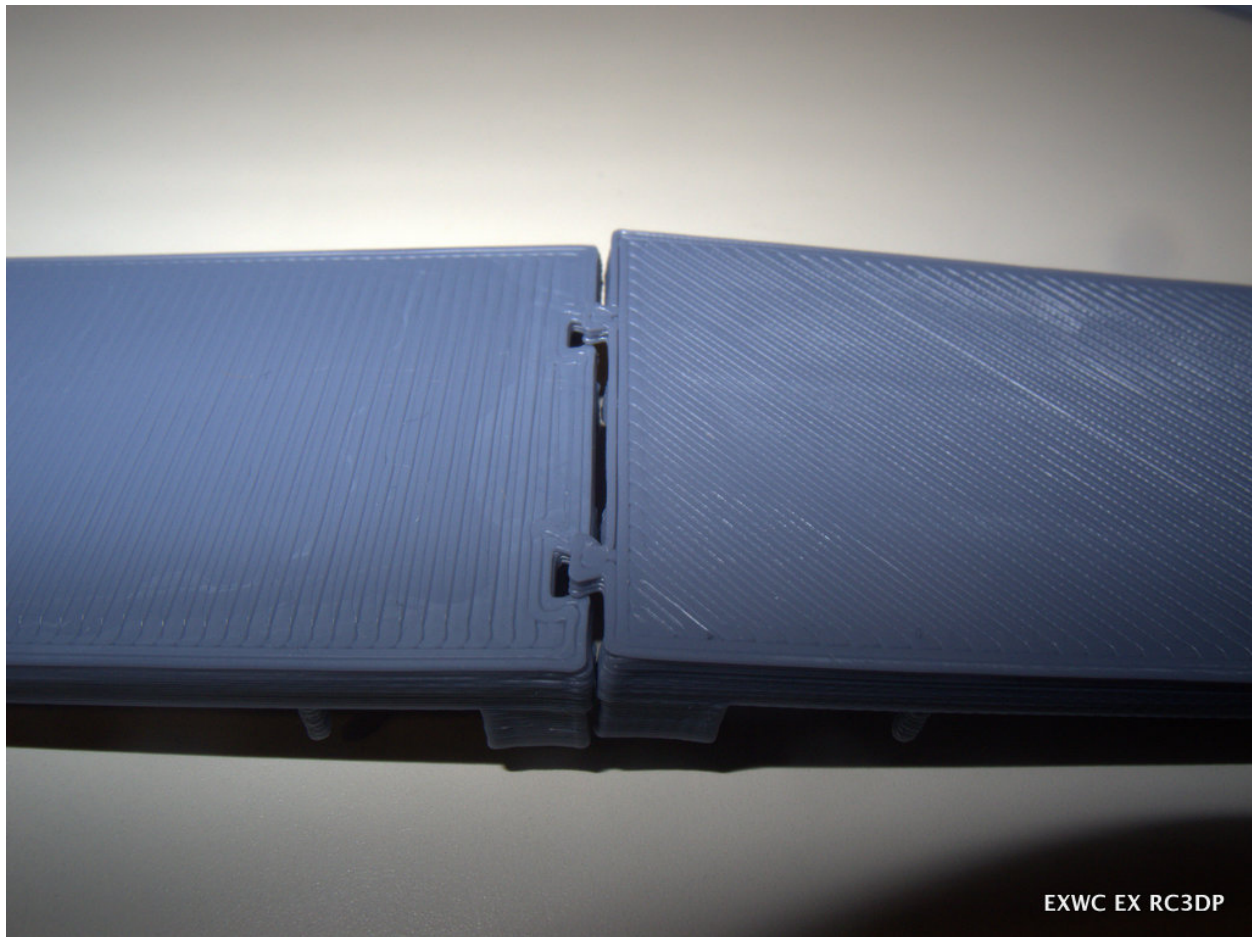
**Figure 19: The warping caused by residual thermal stress, and dimensional overruns did not allow mating of the model sections without manual rework.**

*Pier Print 10 (TAZ5-0013, 0014):* In an attempt to mitigate the warping of the HIPS pier prints, a print of the pier end was attempted with the bed temperature of 60 C. Almost immediately, it was clear that the first layer of the print was not adhering to the build surface and was peeling up at the corners, as seen in figure 20 and 21. The peeling was exacerbated as additional layers were deposited, and the print was canceled. The print was re-attempted with a bed temperature of 80 C, however the same bed-adhesion failure mode was observed.
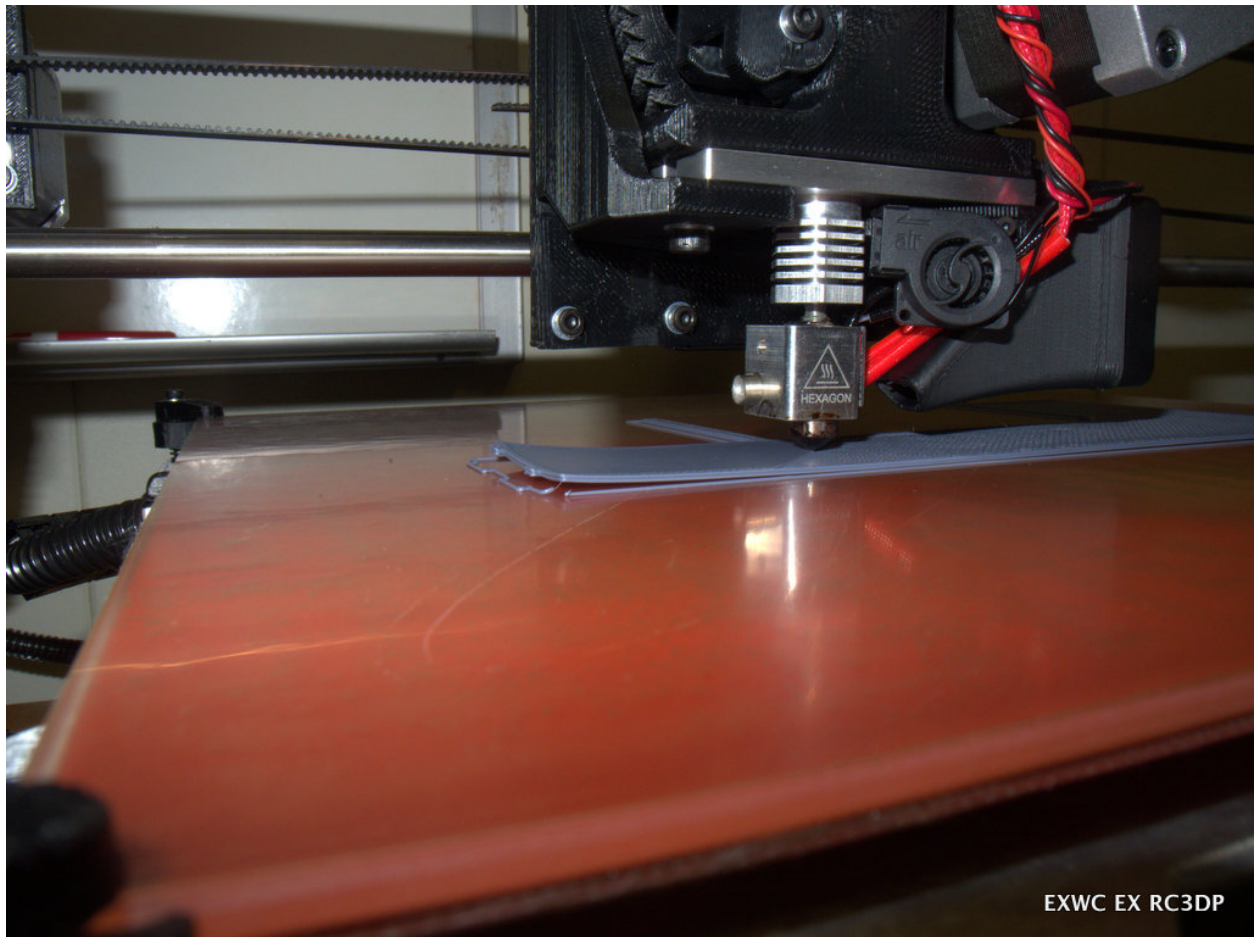
**Figure 20: Early adhesion failure was evident on print attempts at reduced bed temperatures.**

**Figure 21: Attempts to print HIPS parts at reduced bed temperatures resulted in adhesion failures.**

*Pier post processing:* The pier sections as printed would not fit together as designed with the interlocking features. All sections required minor work with a file to remove material overruns and achieve proper mating and assembly. Additionally, it was determined that HIPS parts were able to be flattened through an annealing process for stress relief. A pier section was flattened in a baking pan under a weight (brick), and surrounded by sand to control heat transfer rate, as shown in figure 22. The assembly was baked in an oven at approximately 100 C for an hour, then removed and allowed to air cool. Once cool, the HIPS part was removed from the sand, and revealed to have been effectively straightened as shown in figure 23. Once the pier sections were flattened via the annealing process and the interlocking features were filed to remove excess material, the pier sections fit together precisely, as shown in figures 24 and 25.

**Figure 22: Warped parts were annealed under a weight in a bed of sand to control heat transfer rate and ensure uniform cooling.**
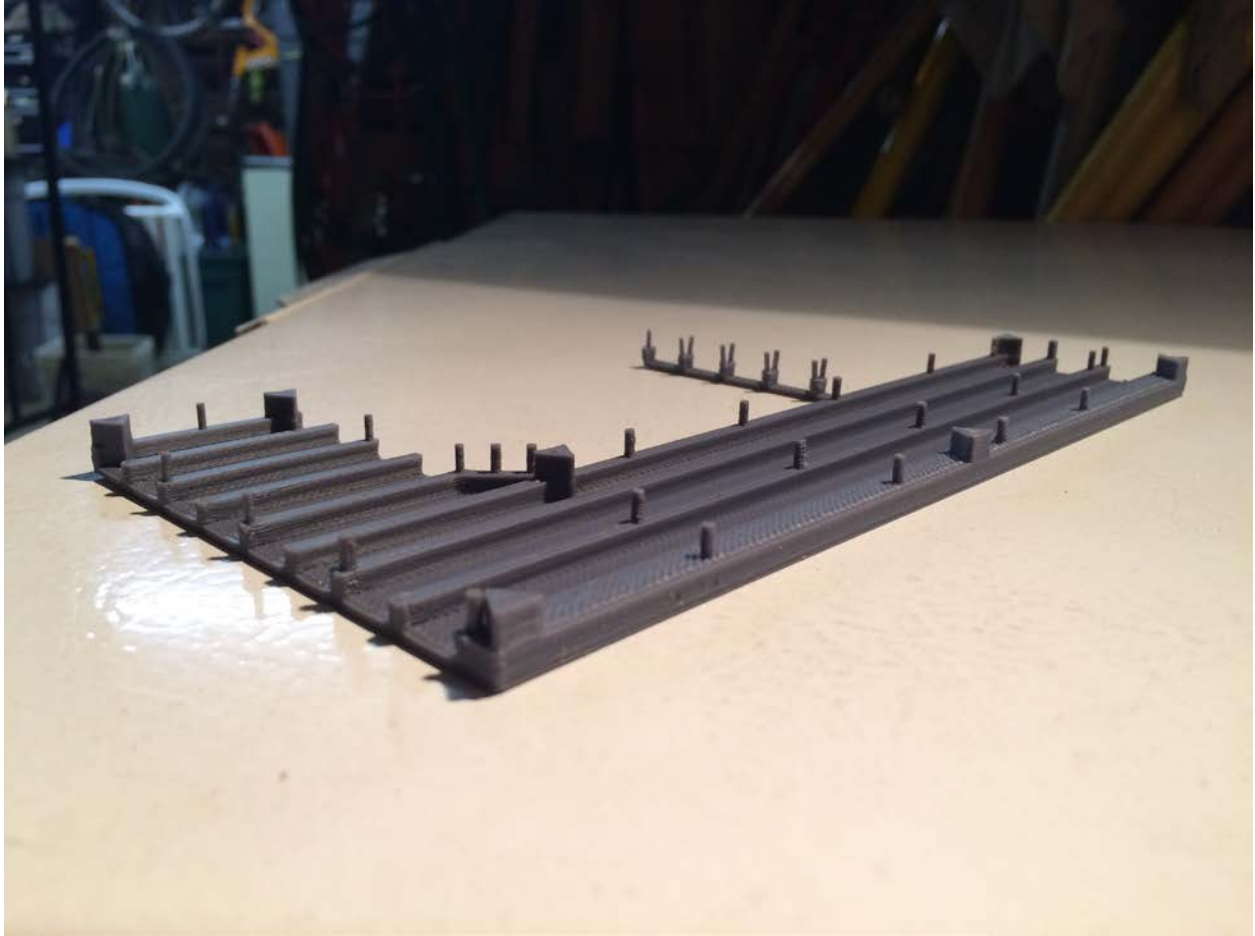
**Figure 23: The annealing process successfully flattened the pier, eliminating the residual thermal stress.**

**Figure 24: The complete pier assembly was assembled after manual fitting and shaping of the interlocking features for proper fitment.**

**Figure 25: Finishing and deburring of the interlocking features was required to facilitate model connection.**


### 5.2. Submarine

File: OR_FULL_M_20150612.dwg

Progress: This model was unable to be opened in AutoCAD 2010, however it was able to be opened in Inventor 2014. As a dwg, Inventor presents a very limited interface. There appear to be no layer controls, and most other command and control options are greyed out or unavailable.

File: WholeBoat10032013-3D.stp

Progress: This model was able to be opened in Inventor and Solidworks, however the sub renders as a transparent object. The sub model is not a closed shape, and cannot be directly exported to print. Additionally, parts appear to have no thickness.

File: OBJECT_OHIO_REPLACEMENT_M_20150624.wrl

Progress: This file is able to be opened using internet explorer. It renders the full shell of a sub, however the shell appears to have no thickness, and several open sections. The file is able to be

loaded by Solidworks, however it renders as a single ring of the hull section and a few of the smaller surface details along the top of the sub. The bulk of the sub is not loaded.

The most progress with the submarine was made from the model that was embedded in the pier .dwg files. Through extensive AutoCAD work, the models were able to be simplified (via the removal of small surface features and extraneous components), and trimmed at the waterline. For unknown reasons, several components within the model were unable to be cut, and the model retained several open features, which presented difficulties in generating a solid model for printing. The sub models were unable to be exported as .stl files from AutoCAD for manipulation in Cura.

### 5.3. Extinguisher Bracket

<u>Files:</u>

- R8611505-96_B.jt
- R8611505-96_B.stl
- R8611505-96_B.stp

<u>Progress:</u>
EXWC is able to open all versions of the part with either Solidworks or Inventor.

*Print (TAZ5-0008):* The .stl file was loaded directly into Cura for slicing and g-code generation, however it loaded as an extremely small component. It was scaled up 10x to achieve a print at a relevant scale to evaluate printer capabilities. The geometry of this part does not lend itself easily to fused deposition modeling, due to the lack of a primary flat surface to use as a base layer. Extensive support material would be required to build the model in any orientation. Additionally, there will be regions of high stress aligned with lay-up planes, resulting in weak areas of the component and easy fracture. The part was printed on the TAZ5 from PLA in a primarily vertical configuration to evaluate a print with both the part and support structure comprised of the same material as shown in figures 26 and 27. The support structure was surprisingly easy to remove and did not significantly detract from the part quality at the supported interface as shown in figure 28. However, the part quickly failed during normal handling, as predicted, along one of the layer interface planes at an area of high-stress shown in figure 29.  A full-scale and significantly more robust component was printed on the Stratasys Dimension as shown in figure 30.
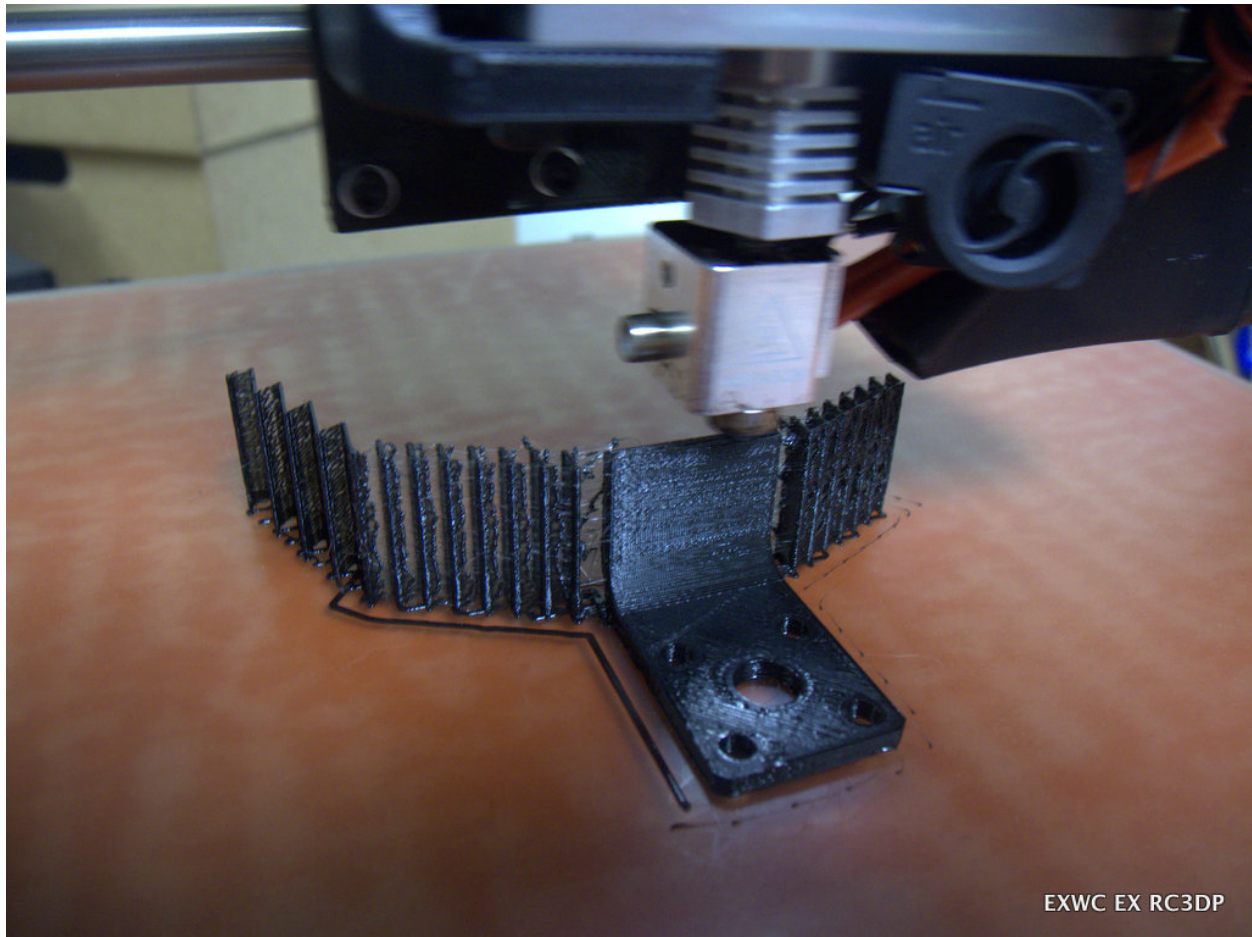
**Figure 26: The partially printed fire extinguisher bracket shows primary and support structure being produced from the same material.**
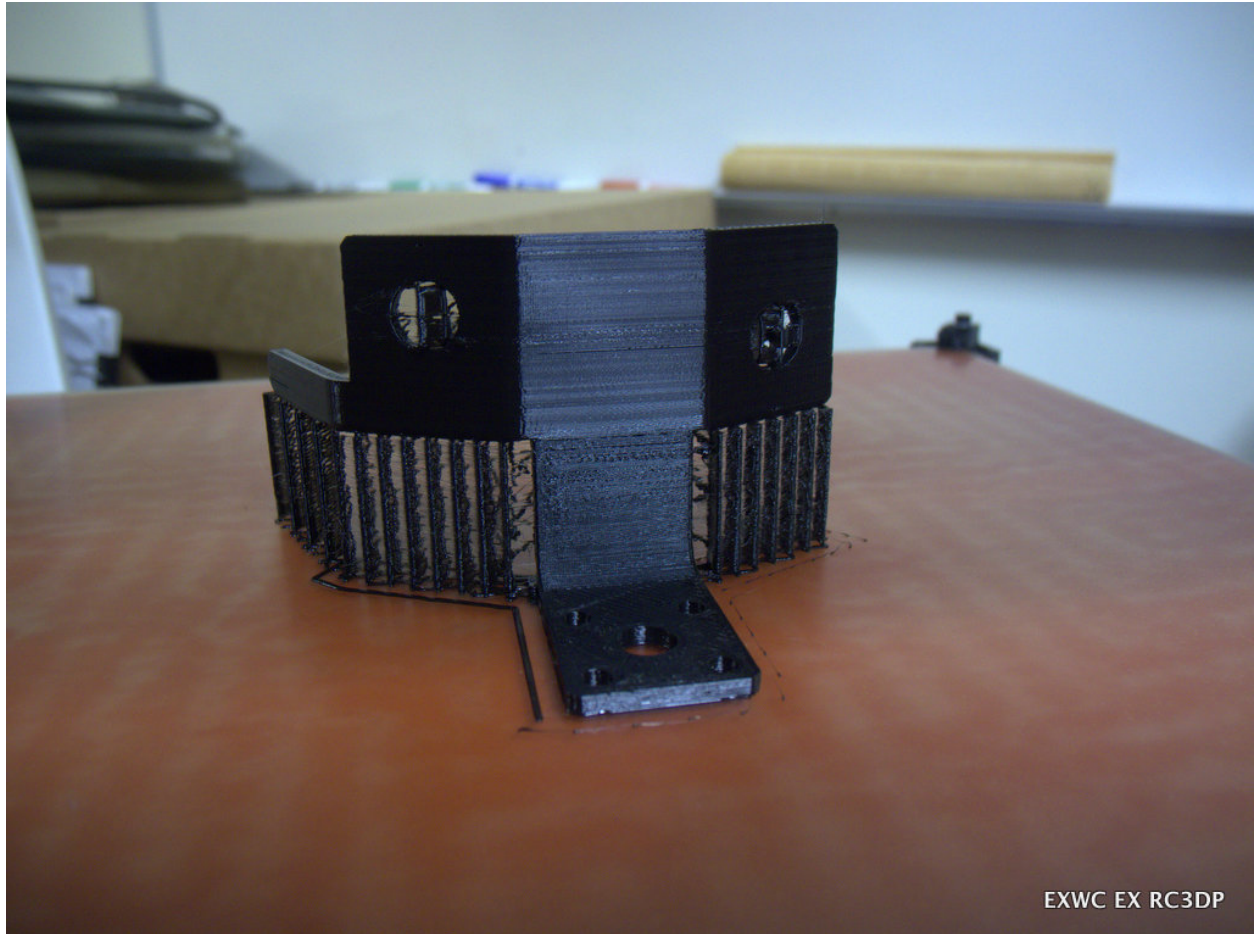
**Figure 27: The fire extinguisher bracket print from PLA on the TAZ5 shows the use of same-material support structures.**
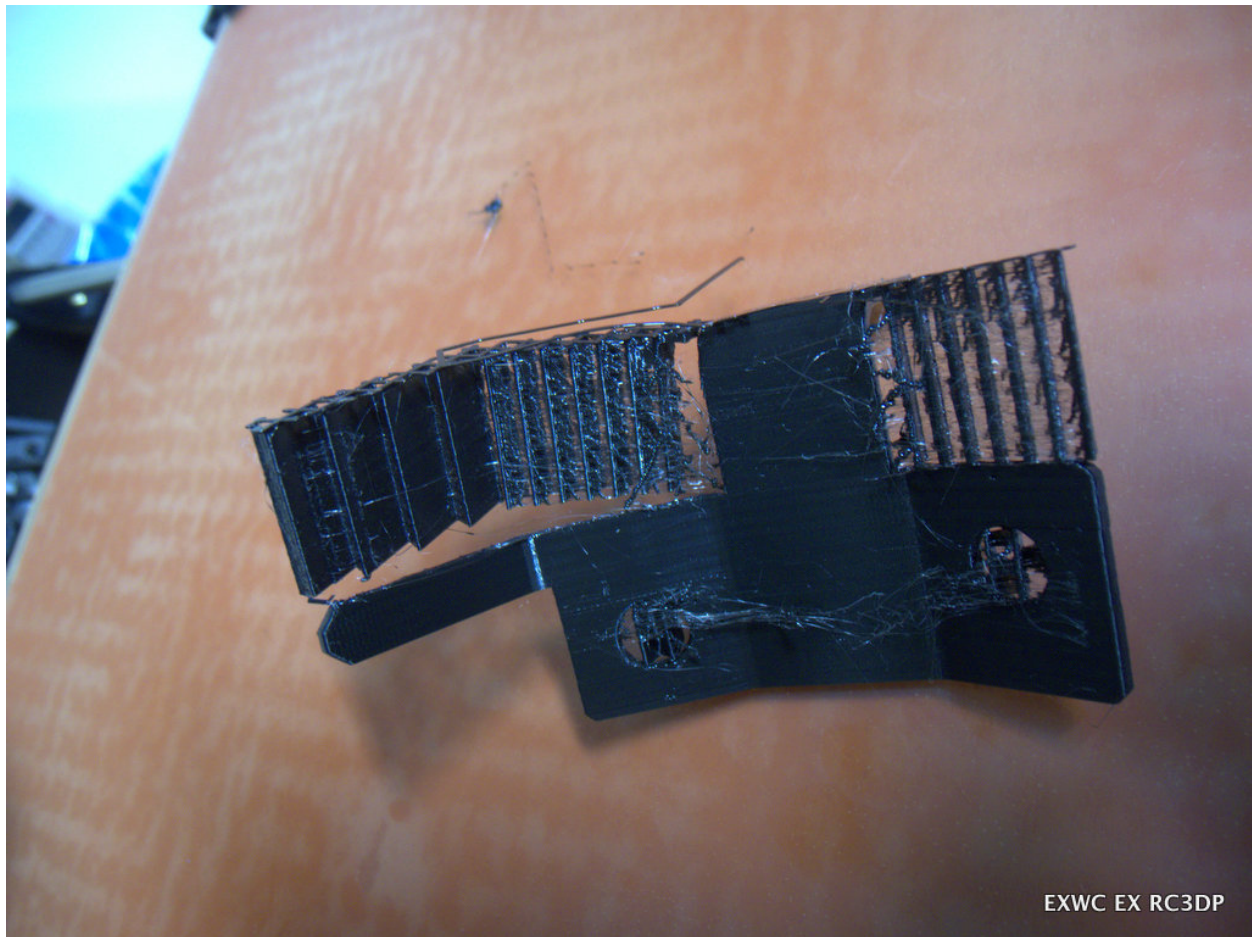
**Figure 28: Deburring of the completed fire extinguisher bracket includes removal of the support material.**
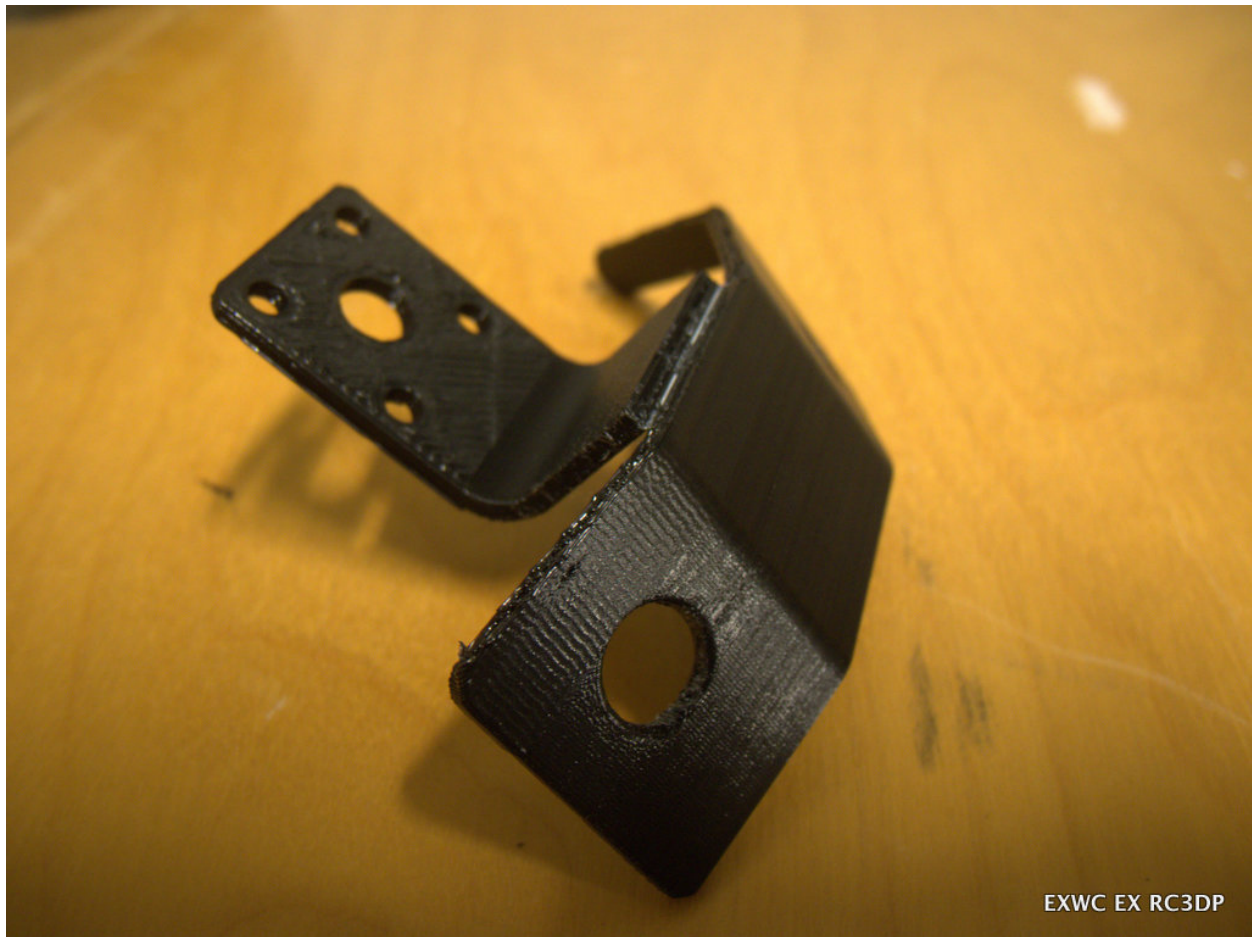
**Figure 29: The fire extinguisher bracket broke along a layer interface at a high-stress area, in spite of delicate handling.**

**Figure 30: The fire extinguisher bracket was successfully printed on the Dimension 1200es. Note the multiple materials and disposable build-plate.**

## 5.4. Other Prints of Interest

*(TAZ5-0015):* As we were unable to generate a file suitable for printing the Ohio Replacement sub, we attempted to download a submarine model from the Sketchup 3D warehouse online repository. An I-400 class Japanese submarine was chosen due to the  apparent high quality of the model. The .skp model file was downloaded, opened with Sketchup, and exported as a .obj file. The .obj was imported into Cura and prepared for print. The original file was revealed to be a surface model, with several open features. Though Sketchup attempted to patch the holes on the .obj export operation, the file still had issues apparent in Cura. When generating g-code, several of the print layers were simply missing. An attempt was made to print the model anyway, and a few of the smaller layer gaps were overcome successfully, however the print totally failed when a large layer gap was encountered as shown in figure 31.
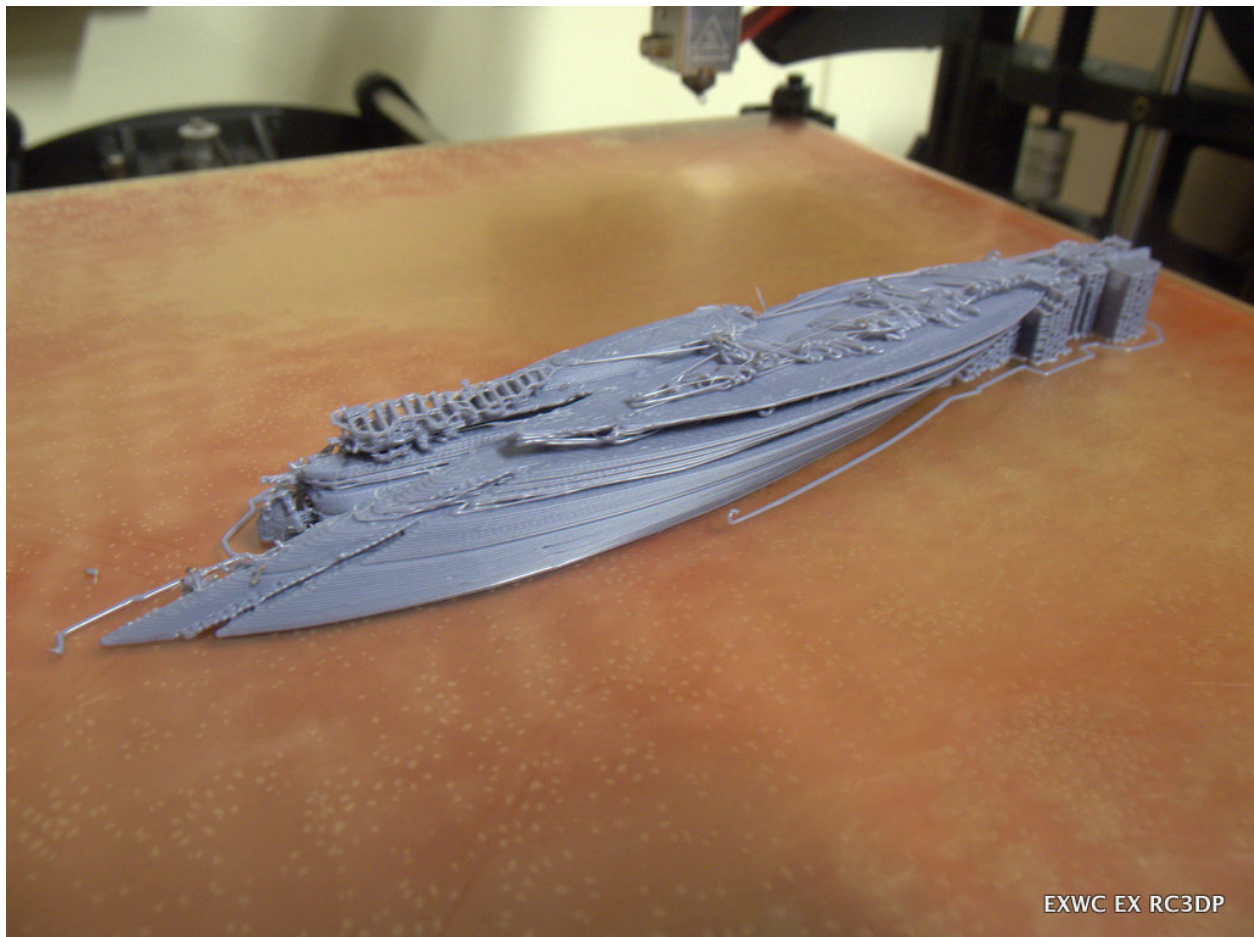


**Figure 31: This print of an I-400 submarine model sourced from the Sketchup 3D Warehouse failed due to missing layers resulting from the conversion from a shell to solid model.**

*(TAZ5-0016, 0017, 0018):* A small shadowbox award for an EXWC high-performing project team was generated in the free Autodesk "123D Design" CAD package (.123dx file format). This model was exported as a .stl file from 123D, and imported with Cura. Cura was able to manipulate the file with no issues. Several versions were printed, with the final print (0018) being a batch-print of 16 parts simultaneously as shown in figure 32. The batched parts came out well, however they all exhibited some bed adhesion failure at the corners despite the 110 C bed temperature, as shown in figure 33.
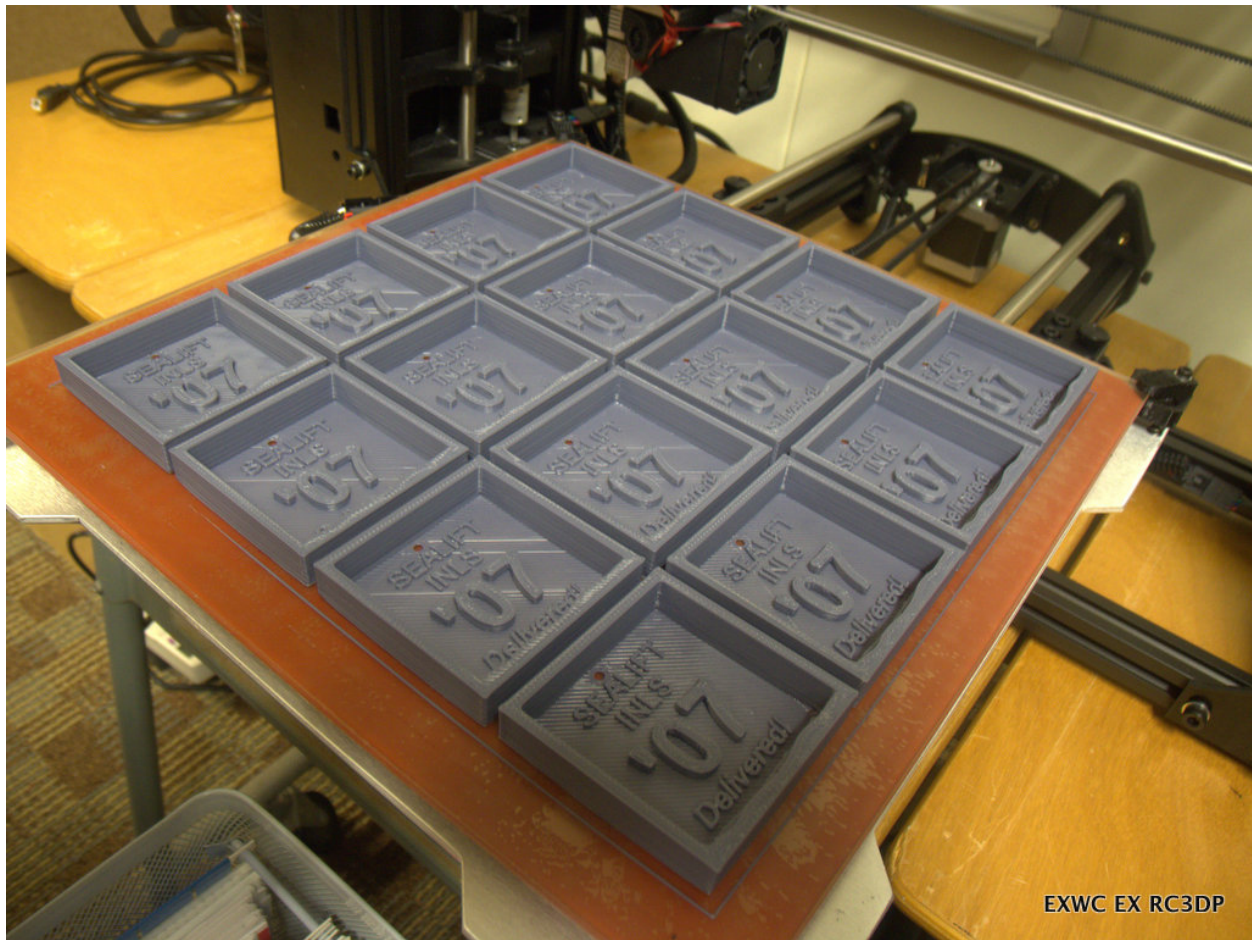


**Figure 32: Batch prints of 16 identical part files were produced to evaluate production consistency.**
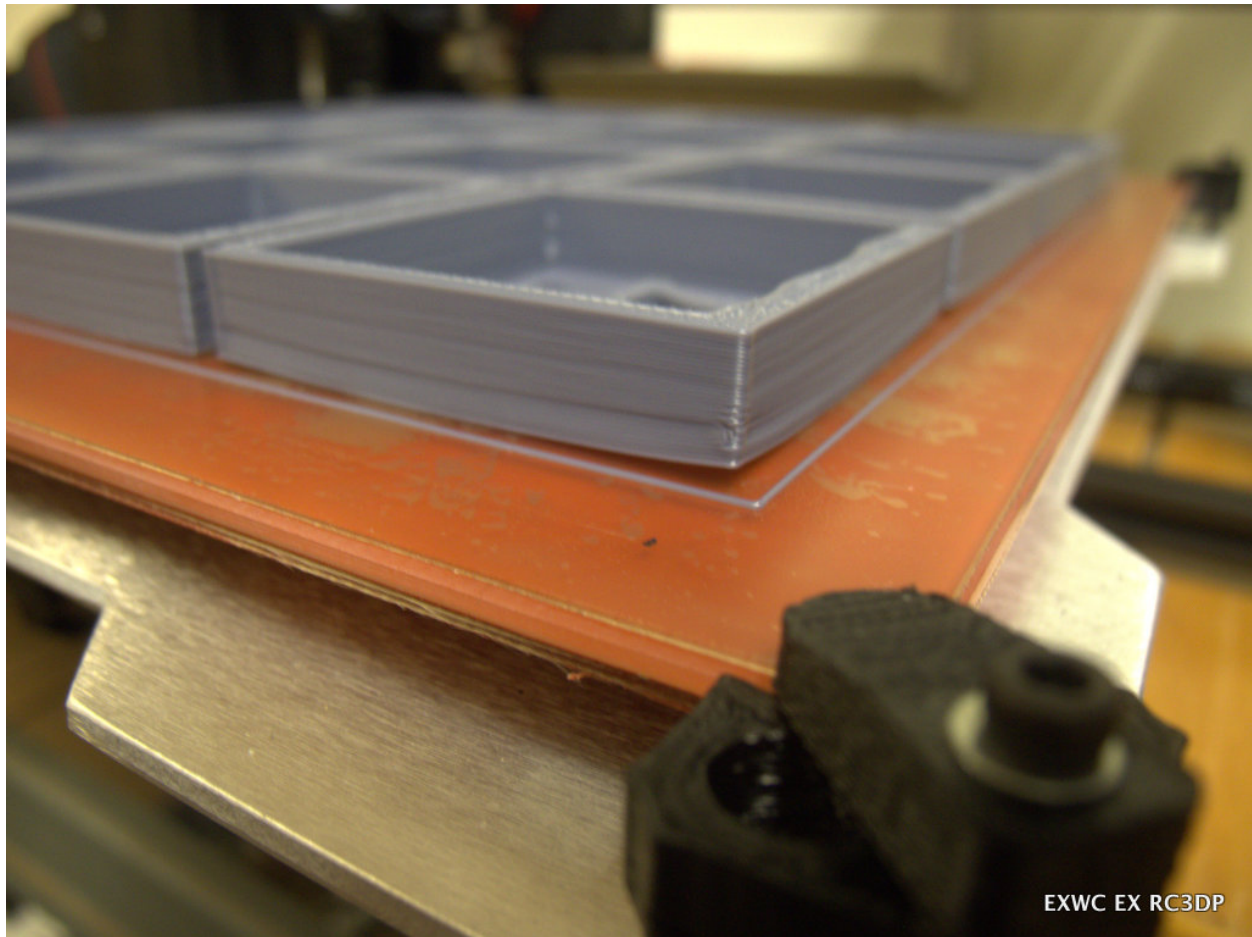
**Figure 33: The batch print of the award shadowboxes revealed minor bed adhesion failure on many of the individual pieces.**

*(TAZ5-0027):* A partial model of the Vanderbilt mansion was supplied as a file with the TAZ5. In order to evaluate printing a facility, with relatively fine details, and near the maximum print envelope of the TAZ5, a copy of the model was scaled to 89x200x170mm (x, y, z). The model was printed in HIPS, on "fast" mode. Printing in "fast" mode resulted in audible stress to the machine. Various popping sounds could be heard on a regular basis from the print head, likely due to the stress of extruding material at a very fast rate. The fast rates of extrusion and of head travel enabled significant bridging capability, wherein certain print features (unsupported spans) that would have required support material on finer quality settings were able to be bridged without any support, such as the door header in figure 34. However, a few features still failed on the print due to the lack of support material, as shown in figures 35, 36, and 37. The fast extrusion rate may have also reduced the filament temperature, as there were several areas on one side of the print where inter-layer cracks appeared during the print, indicating weaker than normal layer bonding as seen in figures 37 and 38. These cracks did not prevent the completion of the print, and it is strange that they occurred only on one side of the part. This is likely due to the position of the nozzle cooling fan, and the increased ambient cooling airflow  that side of the part during the print operation.
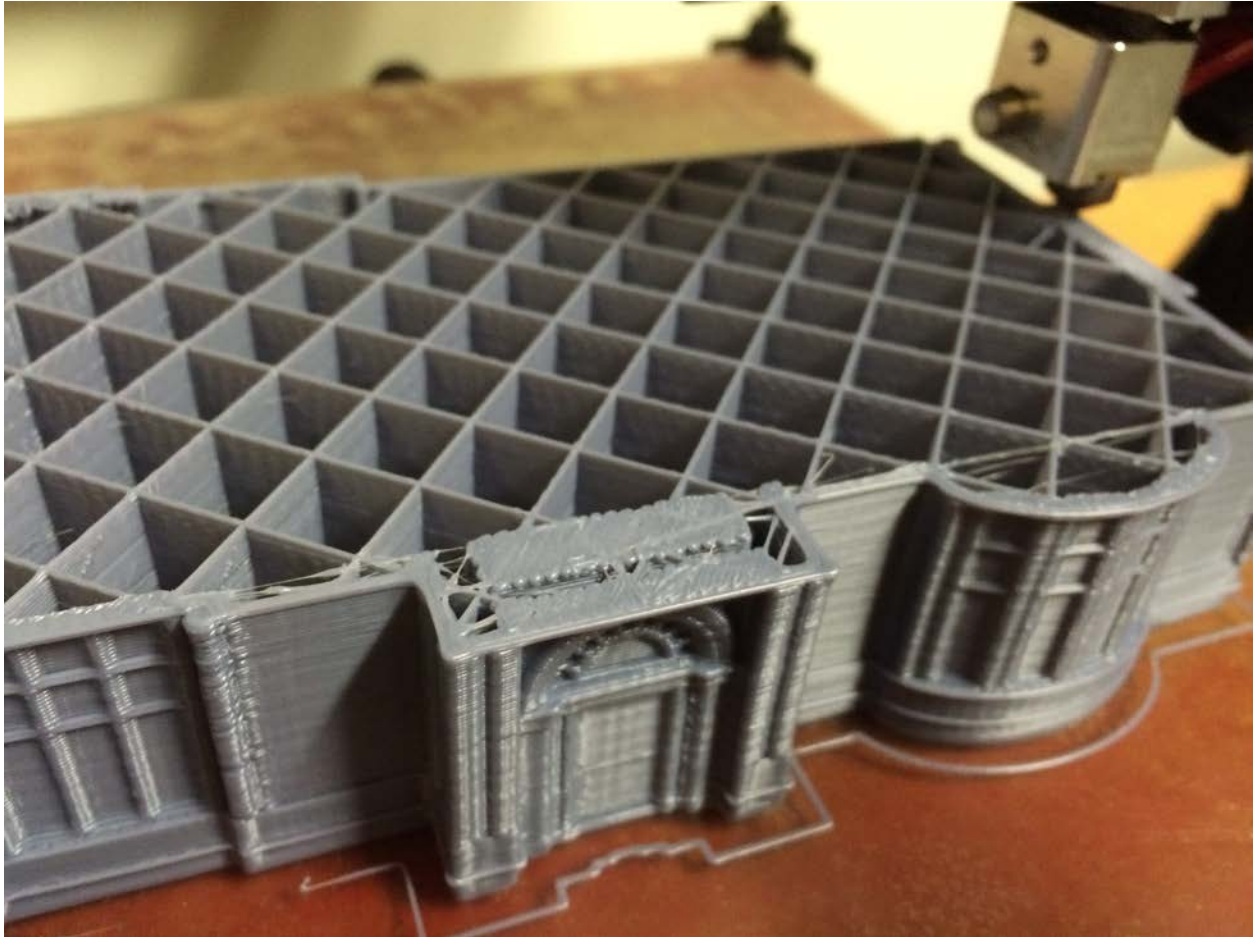
**Figure 34: This view of the partially completed Vanderbilt mansion print shows a door header which was successfully bridged without support material, enabled by the fast print speed and thick filament extrusion.**
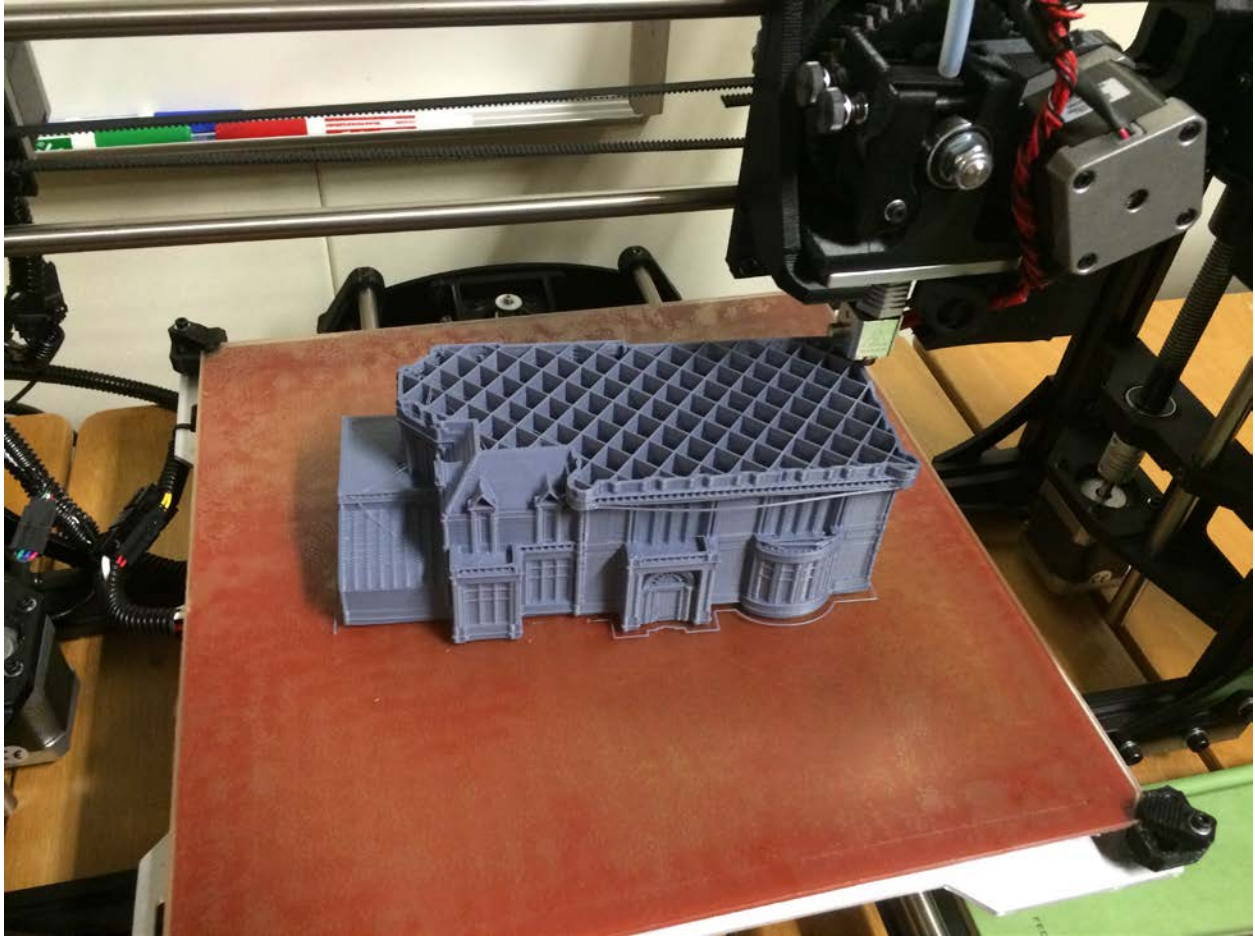
**Figure 35: This image of the partially complete Vanderbilt mansion shows the uniform internal support structure.**
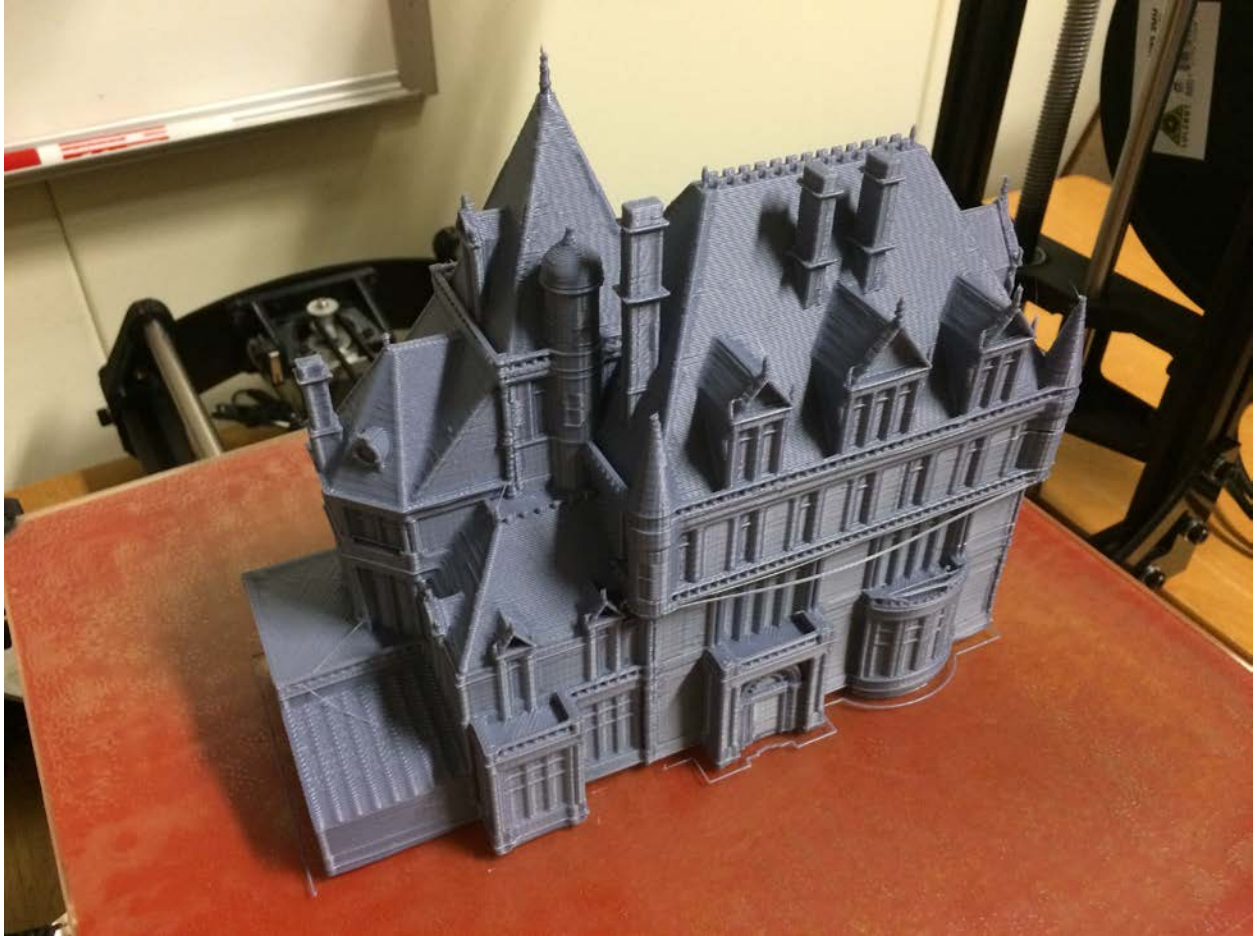
**Figure 36: The completed Vanderbilt mansion print is the largest print to-date on the TAZ5 printer at EXWC.**

**Figure 37: This surface detail of Vanderbilt mansion print shows unsuccessful elements of the print due to lack of support material.**

**Figure 38: The surface detail of Vanderbilt mansion shows cracking and delamination, likely as a result of thermal stresses and poor layer adhesion at fast print speeds without optimized or adjusted temperature parameters.**

*(TAZ5-0030):* McMaster Carr is a large industrial and commercial supply company with an extensive catalogue of tools and parts. McMaster.com provides free downloadable solid models of many of the parts that they stock and sell. To evaluate a variation of the digital workflow, a small part was chosen to be downloaded and printed. A pipe end cap was selected as a small part, with specific dimensional requirements, and interesting features such as threads. The part was downloaded as a STEP file, opened in Autodesk 123D design, exported as a .stl file, prepared in Cura, and printed without any issue as shown in figure 39. The part was printed as a complete solid with no fractional infill. The internal threads were able to be printed without any support material. Note: this part was purely a workflow and complex-feature print experiment and is NOT intended for, nor capable of use as an actual pipe end cap. Given the print orientation, inter-layer bond strength, and porosity of printed material, the finished part is not suitable for actual use. This serves as a perfect example of a potential danger of inexpensive, distributed advanced manufacturing technologies. Just because one can print something does not mean that one should, and a non-engineer may unknowingly print a replacement part or component that does not meet the appropriate design requirements.

**Figure 39: This pipe end cap was downloaded as a model file from McMaster Carr, and printed in ABS plastic on the TAZ5.**

# 6. EMPIRICAL OBSERVATIONS AND LESSONS LEARNED:

### 6.1. Material Performance

- PLA prints exhibited a smooth, shiny surface finish, however small features exhibited by residual flash, requiring extensive deburring as shown in figure 40. Additionally, printing with PLA resulted in noxious fumes near the printer, highlighting the need for appropriate ventilation and environmental conditioning of the workspace.
- HIPS prints exhibited a smooth, high quality surface finish and no flash or other undesired residuals as shown in figure 41. Print operations produced very little odor.
- ABS prints exhibited a clean surface finish with very little flash or other undesired residuals as shown in figure 42. Print operations produced very little odor.
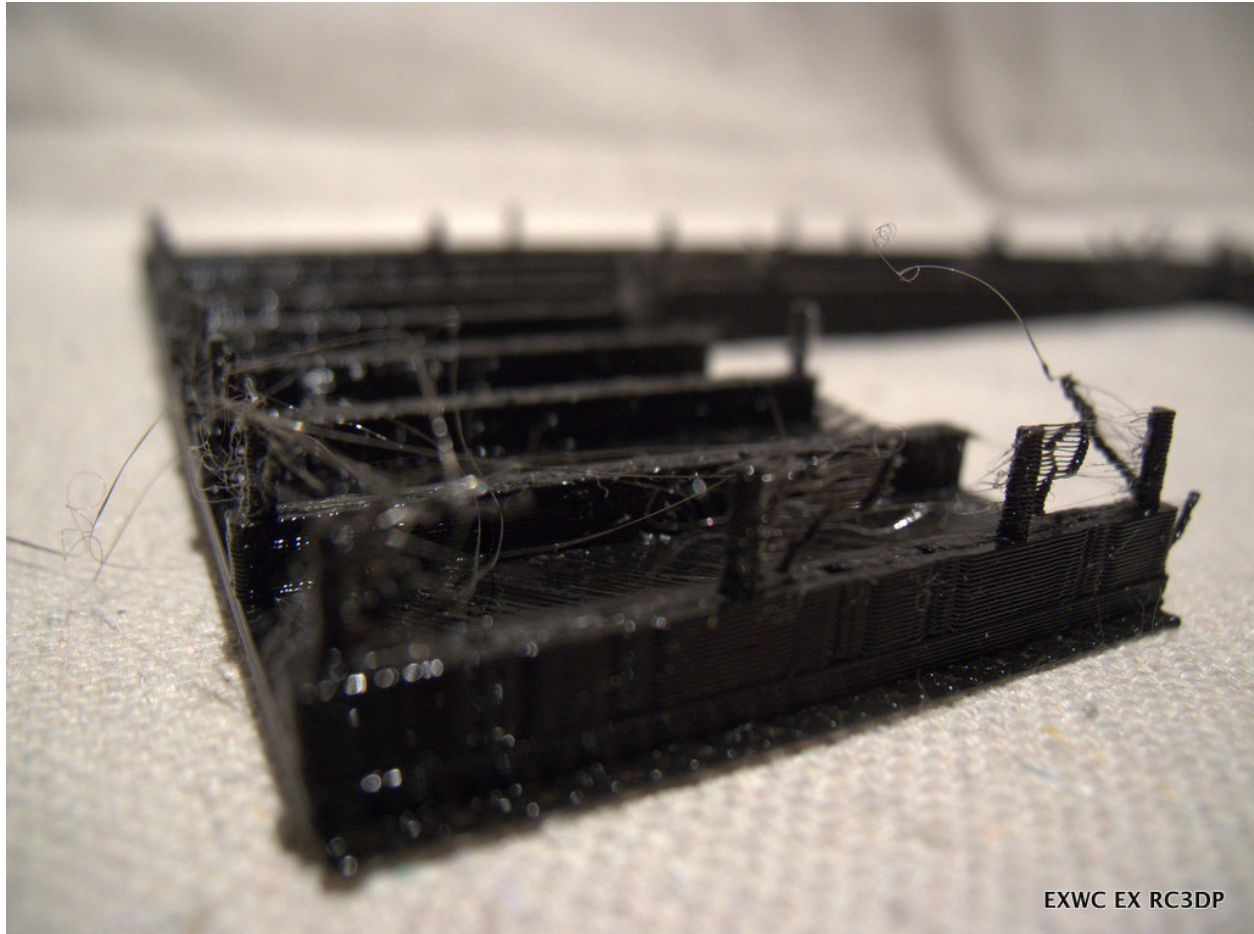
**Figure 40: Early PLA prints resulted in extensive flash and filament trails, requiring significant deburring.**
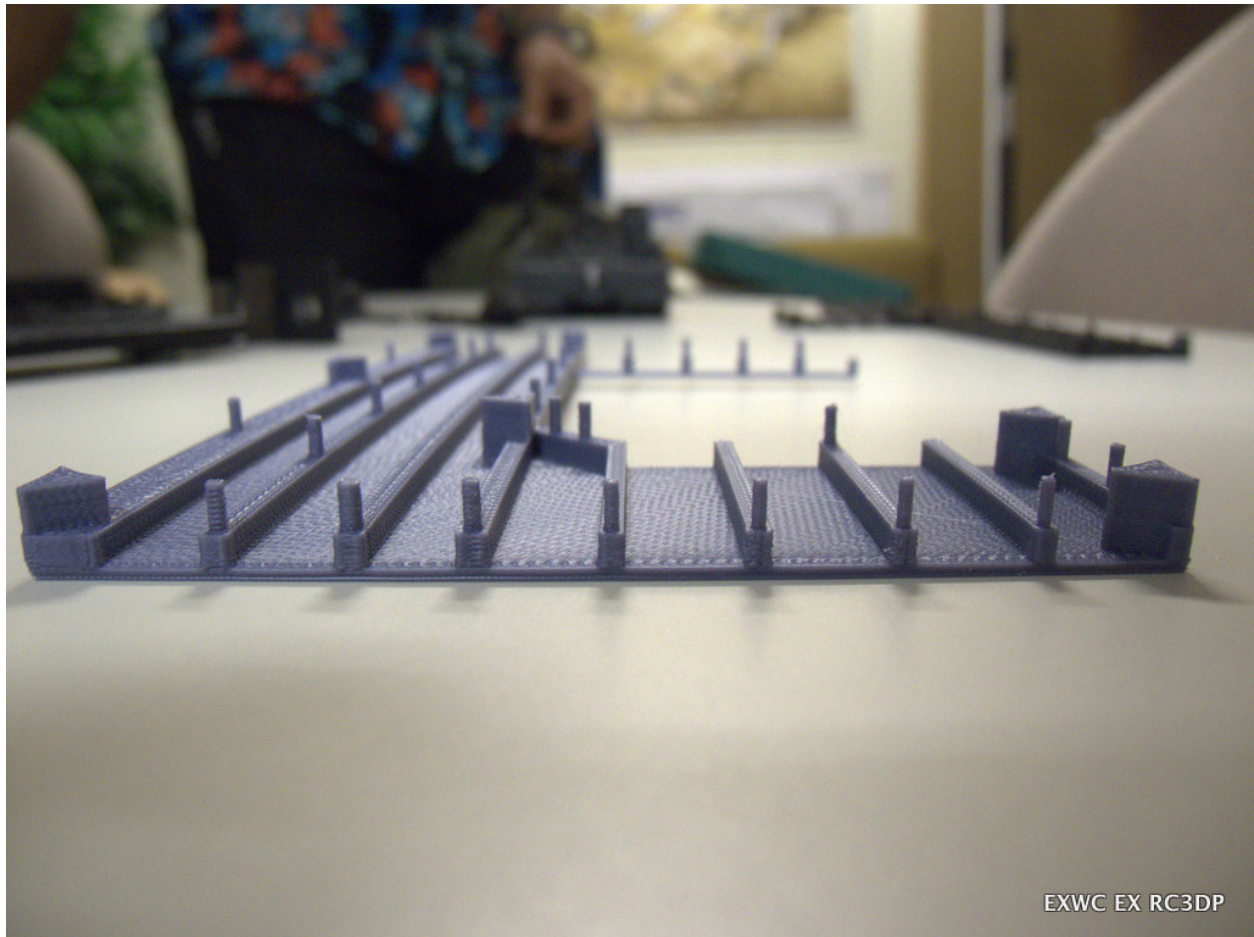
**Figure 41: This HIPS print shows an extremely clean finish requiring no deburring.**
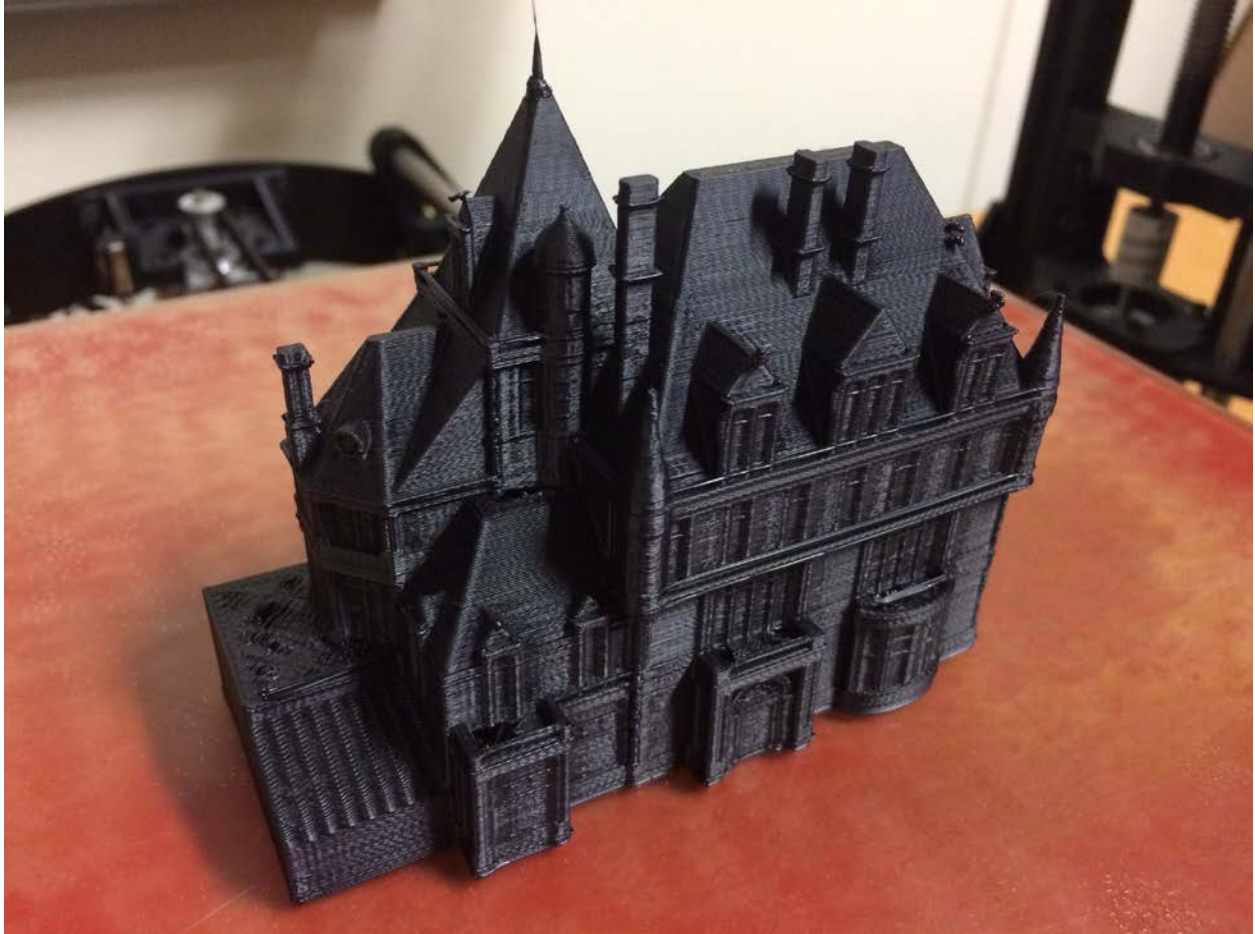
**Figure 42: This small ABS print of the Vanderbilt mansion shows good surface finish and no flash or other production residuals.**

### 6.2. Print software file handling

Each printing software handled files slightly differently, and provided different levels of capability towards achieving the desired print result. Specific differences and nuances include:

- Most of the slicing engines accommodate support material using a single print-head system by generating a rectilinear support scaffolding structure with very limited contact points underneath any overhanging part features. Autodesk Print Studio produced a completely different type of support material, exhibiting a tree-like organic form with a main trunk and many branches at the top of the structure as shown in figure 43. The single print attempt of a file with this type of support failed when the printer head knocked over one of the tree-like structures.
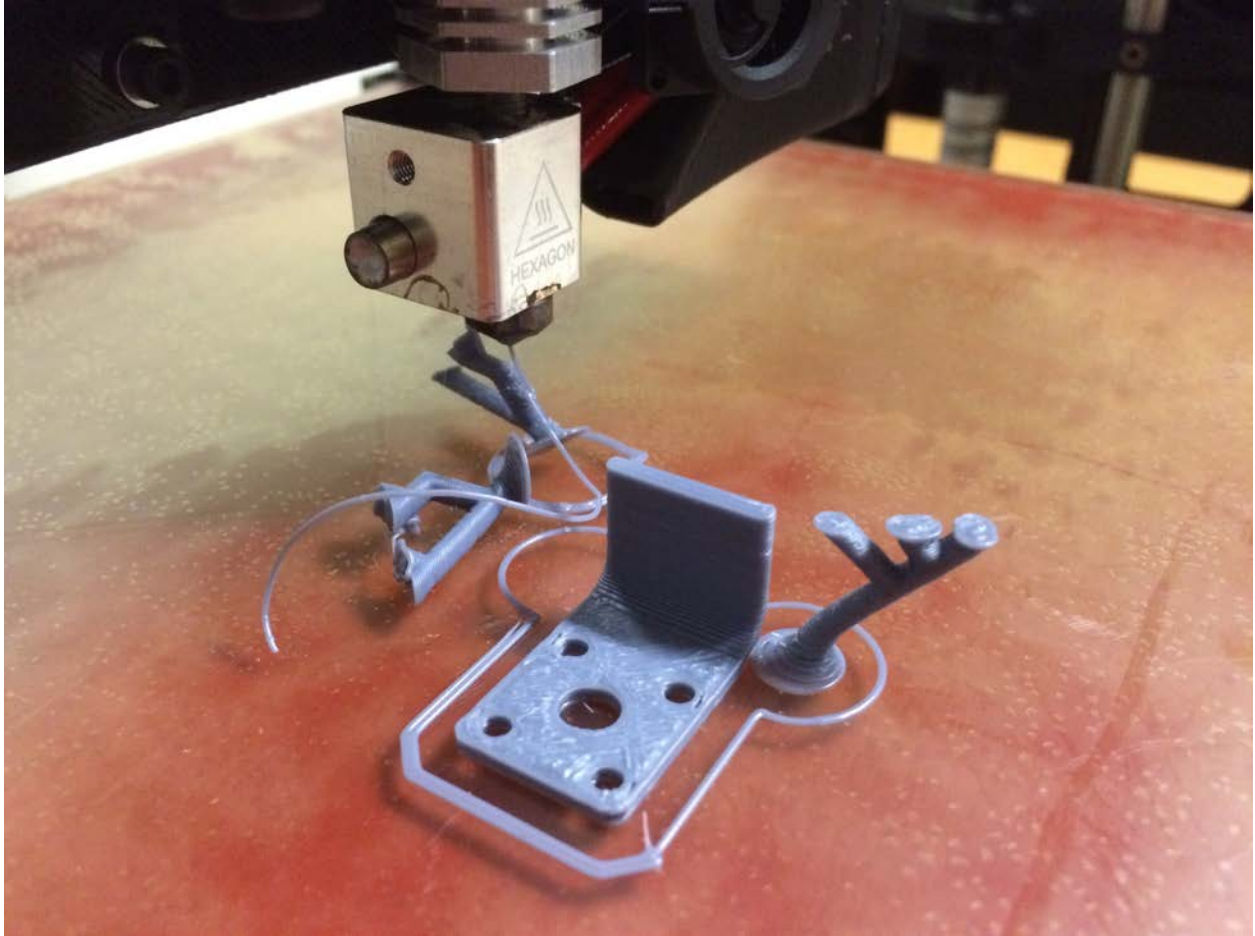
**Figure 43: Autodesk Print Studio produces organic support material shapes, as shown in this print of the fire extinguisher bracket. Note that the print failed when one of the supports was knocked over.**

- Each slicing engine provides different alternatives for infill geometry. All engines can generate rectilinear infill, however some can produce honeycomb, concentric, spiral, zig-zag, and other unique patterns. Cura is limited to a continuous rectilinear square infill pattern shown in figure 44. Slic3r has options to produce a wide variety of patterns listed above, and a honeycomb pattern is shown in figure 45. Autodesk Print Studio produces a linear array that alternates 90 degrees each layer as shown in figure 46, and employs organic forms for parts support structures. The resulting rope-cleat part produced form the Cura file can be seen in figure 47, and the de-burred part can be seen in figure 48.
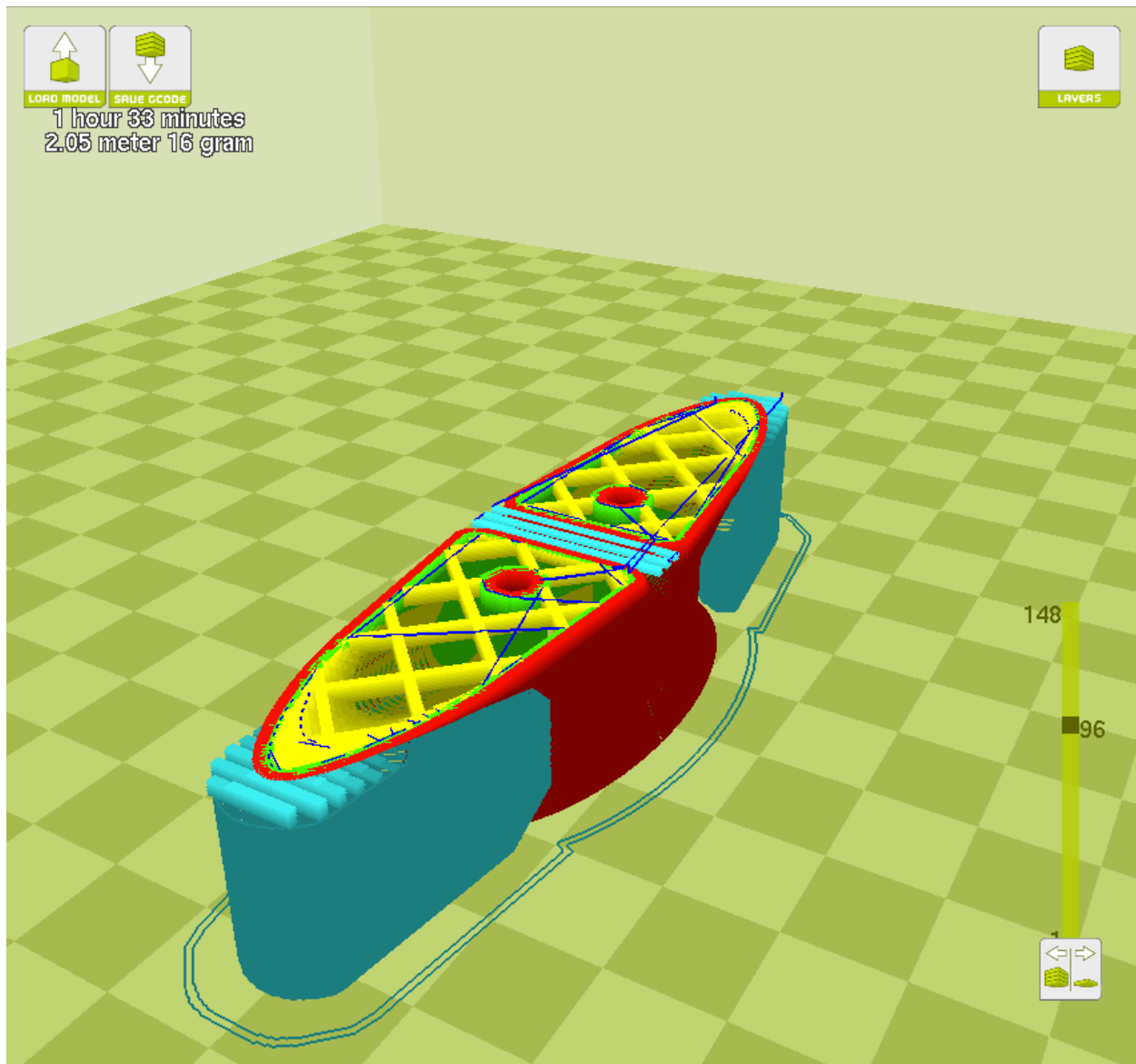
**Figure 44: This Rope Cleat screenshot from Cura shows a square infill pattern and linear support material.**
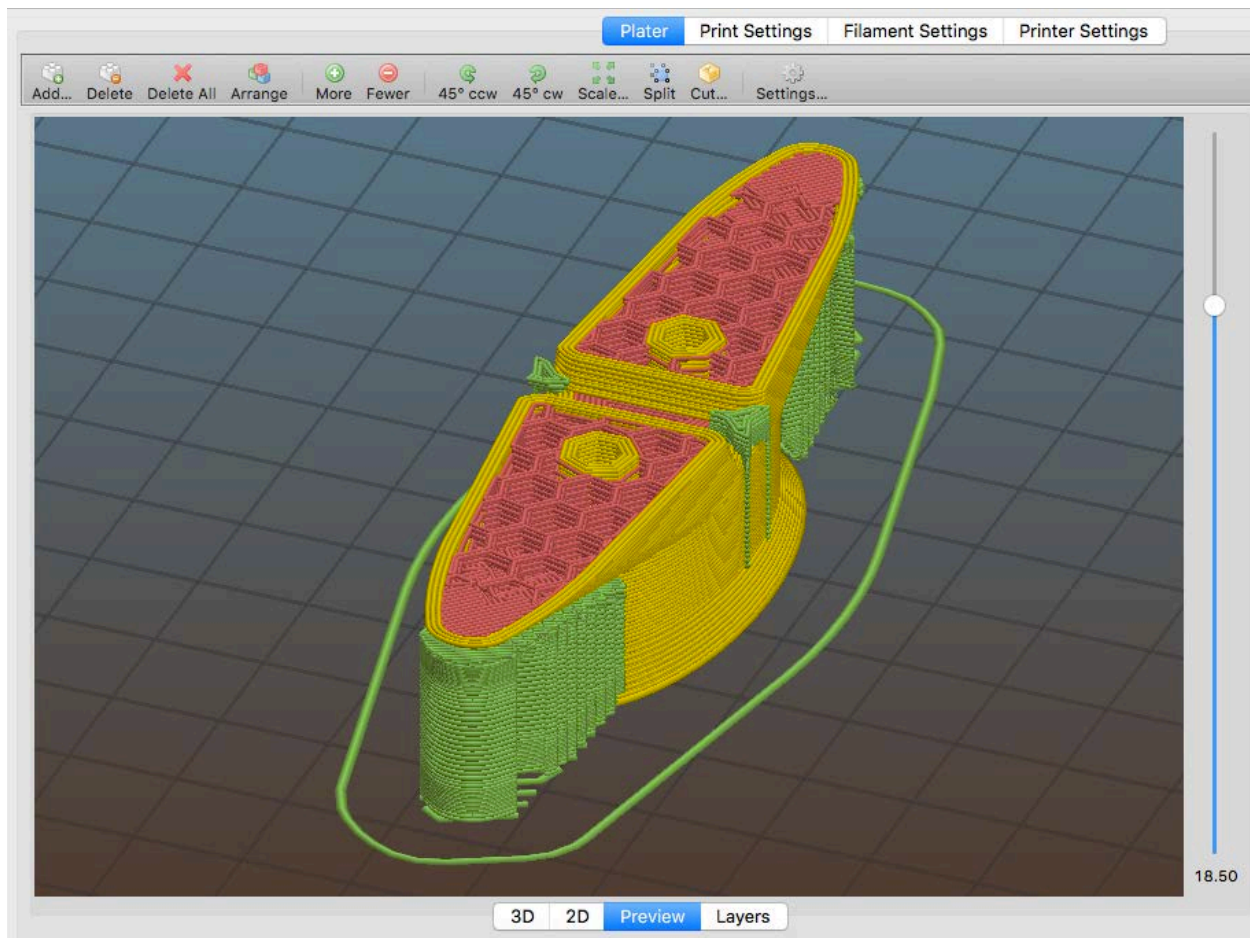
**Figure 45: This Rope Cleat screenshot from Slic3r shows hexagonal infill pattern and linear support material.**
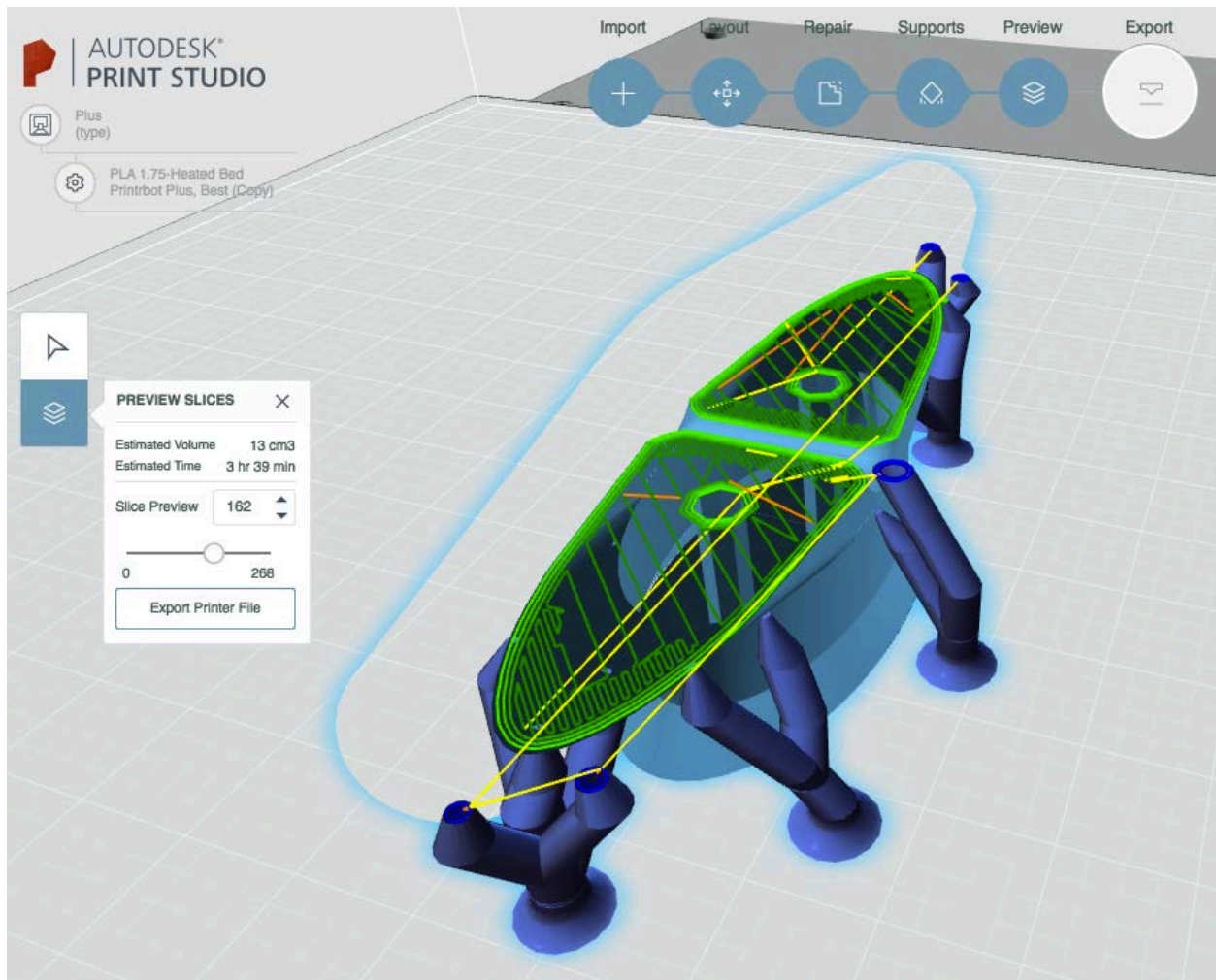
**Figure 46: This Rope Cleat screenshot from Autodesk Print Studio shows alternating linear infill pattern and organic-type support material.**
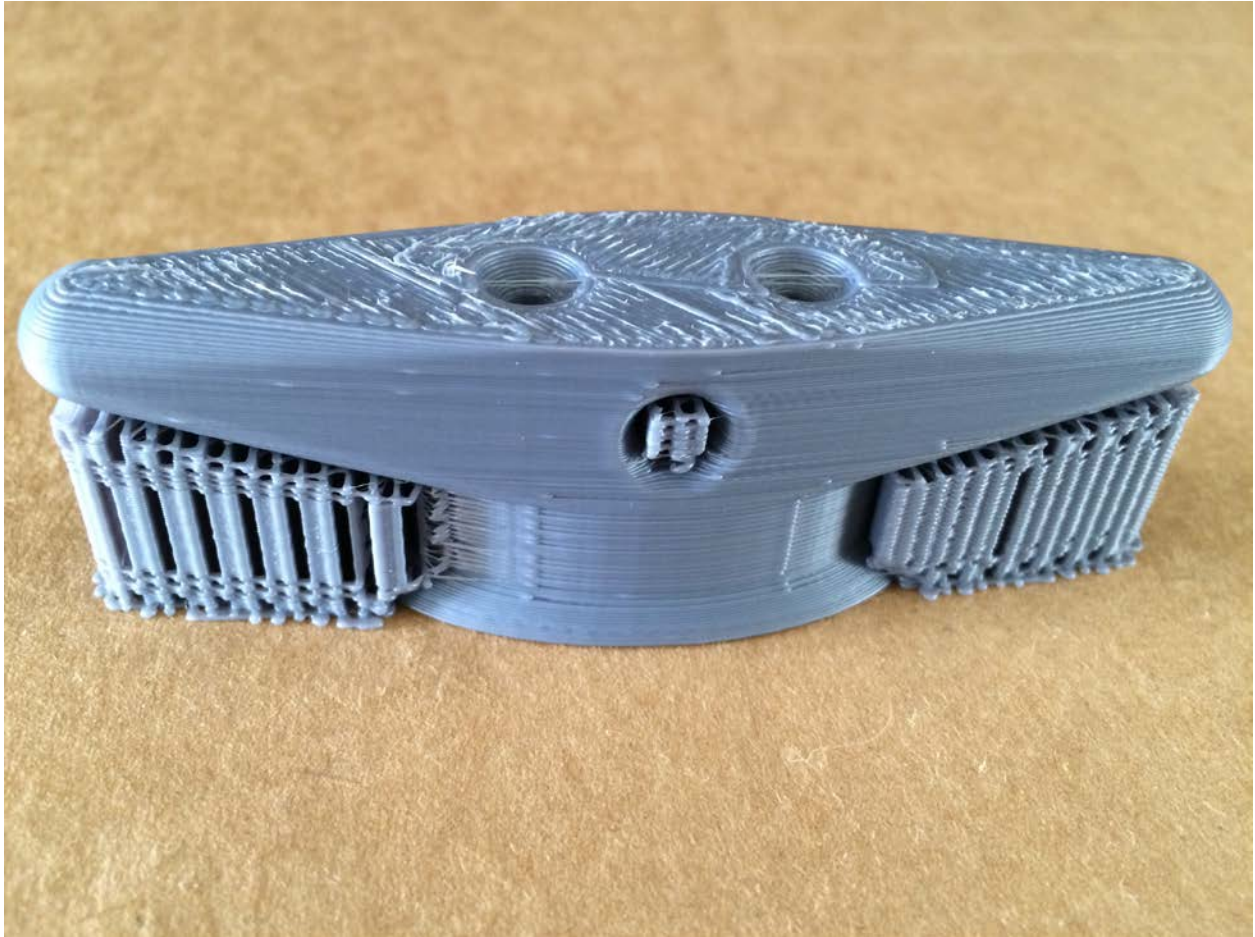
**Figure 47: This print of the rope cleat shows the extent of support material generated by Cura to support the overhanging model areas.**
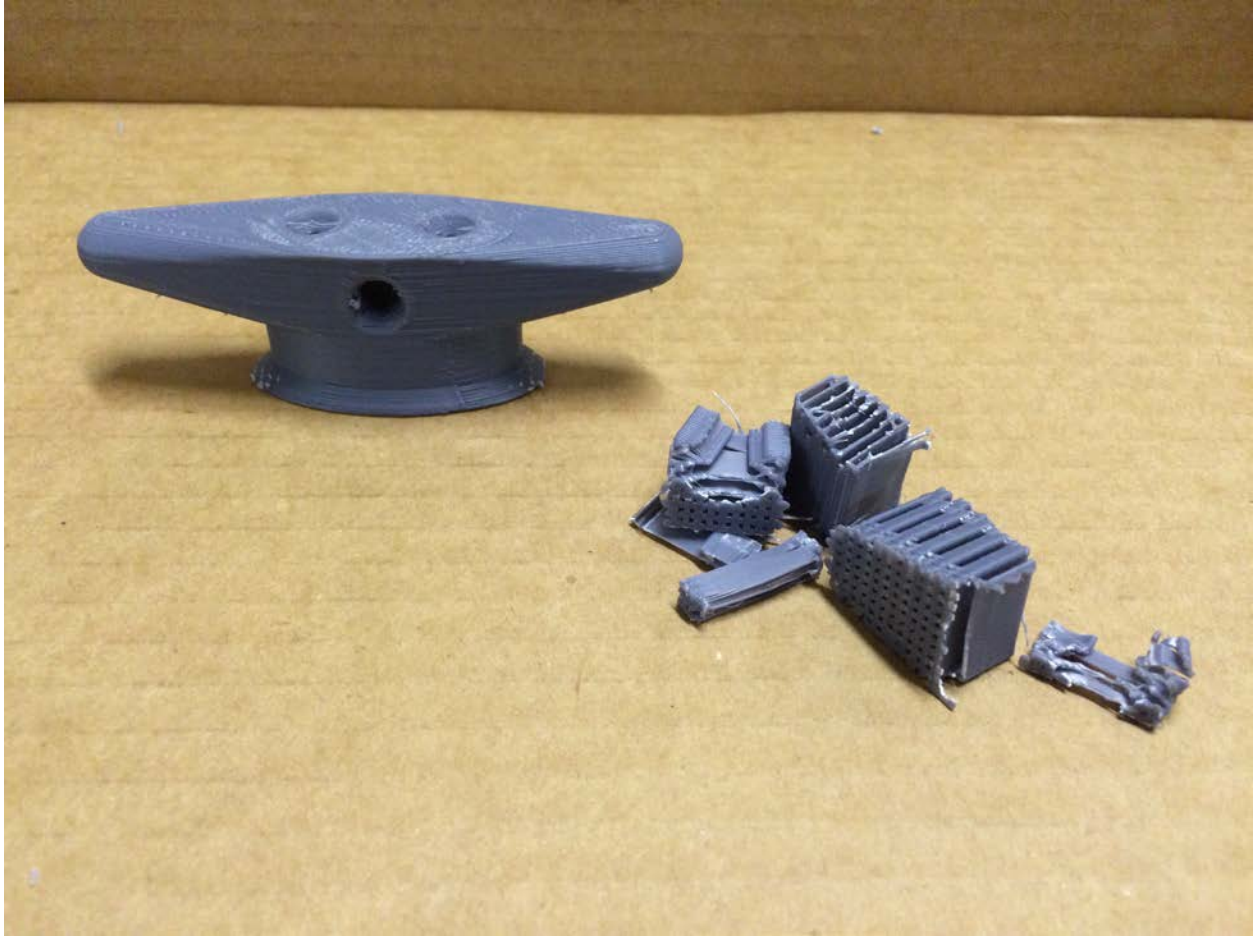
**Figure 48: The support material is easy to strip from the actual part and does not significantly degrade part finish quality.**

- Blender was able to simply and easily convert x3d files to both .obj and .stl files through Import and Export commands, with very little loss of quality or detail smoothing. No other software was able to handle and convert .x3d files.
- Autodesk Meshmixer was able to repair .stl files that Autodesk Print Studio was unable to fix, however the resultant output was affected by feature smoothing and significant loss of detail.

### 6.3. Residual Thermal Stress and Warping

As a result of the printer configuration, with a heated bed and open build volume, parts produced on the TAZ5 exhibited significant residual thermal stress, resulting in post-production warping as shown in figure 49. This warping was observed on all parts except those with very high section moduli. Fortunately, a post-treatment annealing process proved successful, wherein the warped components were flattened, buried in sand to control heat transfer, and baked in an oven. This was proven to correct the thermal distortion and was used effectively to

repair several pier and sub sections. This residual thermal stress is a non-issue with the Stratasys machine due to the enclosed build volume and the single-use non-heated build plate. A potential solution to the warping issue on the TAZ5 may be to build warp-prone parts on a complete raft of support material, isolating the base layer of the part from the heated build plate. Another option may be to numerically model the residual thermal stress and resulting warping, and modify the part design such that the part effectively warps itself flat (however, this would be very difficult given the linear nature of the FDM layer deposition process, and the uneven thermal profile through the z-height of the part).
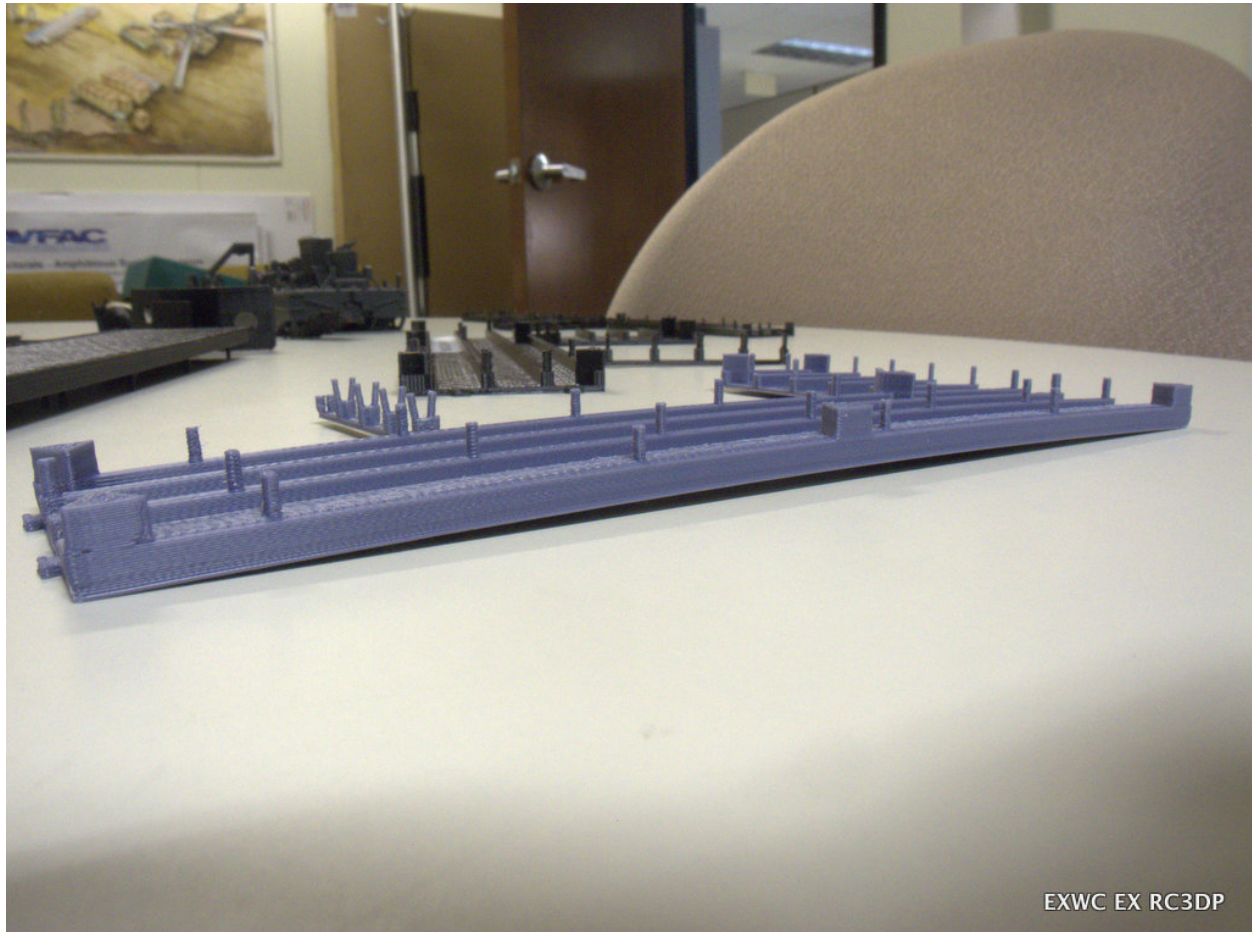


**Figure 49: This HIPS print of the pier shows the warping caused by residual thermal stress.**

### 6.4. Simultaneous Multiple-Print Operations
Several multiple-print operations were executed (TAZ5-0018 INLS shadowboxes, and TAZ5-0031-0033 Rocktopus), and important phenomenon were observed with each. Though the arrayed models of the parts may be identical in software, each part produced by the printer is unique. This is a result of the automatic tool-path generation that the slicing engines produce. Each part on the build plate may have different start and stop coordinates for each layer,

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resulting in unique part appearances. The overall shape of parts is identical for all intents and purposes, but it is clear that the start/stop "seam" is in a different place on each part resulting in a difference of appearance as shown in figure 51. Additionally, each part exhibited different bed adhesion issues and regions as shown in figure 50. Nearly all of the parts printed in the array showed some level of bed adhesion failure at the corners, but the extent and area on each part was slightly different. None of the bed adhesion issues resulted in print failure.
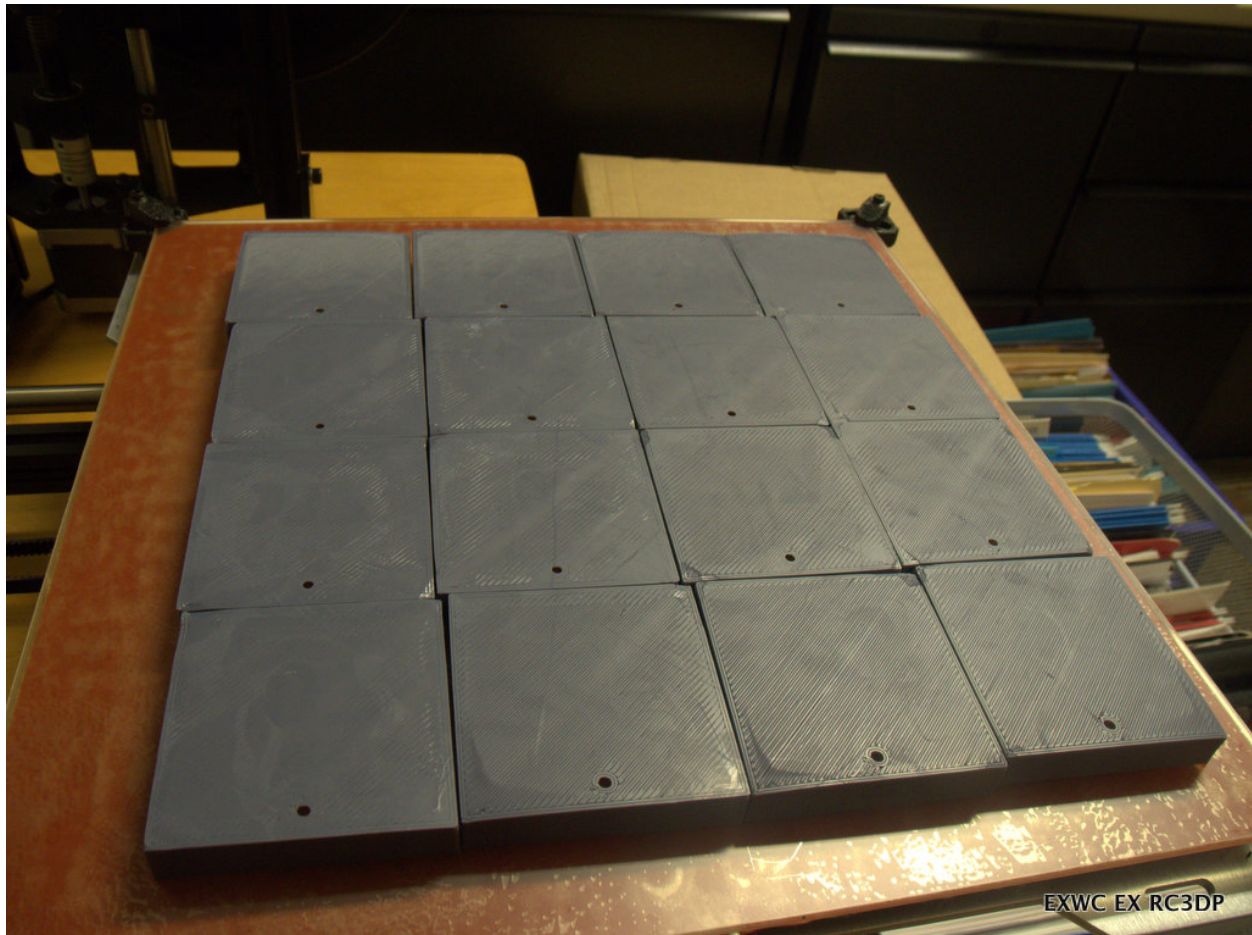


**Figure 50: The bottom side of a batch print operation reveals multiple instances of bed adhesion failure in the corners, however this did not compromise the print.**

**Figure 51: The batch print operation of the "Rocktopus" model revealed that each instance showed minor variation based on extrusion start/stop points.**

### 6.5. Equipment Setup and Maintenance

Proper equipment setup and maintenance is critical to ensure production of quality parts. The following observations were recorded in reference to the TAZ5 printer.

- It was observed on initial setup that the bed travels past the extents of the guide rails, requiring that the machine be set up in a position where the bed will not crash into walls or other items on a desk.
- Due to a variety of factors including thermal cycling of the build surface and mounting hardware, the bed must occasionally be re-leveled to be co-planar with the print head. The bed level is easily checked by positioning the print head at each corner of the bed, and using a piece of paper as a drag gauge to ensure that there is equal head standoff at all four corners. The bed is easily leveled by the use of a hex-key on the bed-mounting feet.
- The machine should be warmed up before each print job, by waiting for the print surface and extruder head to come up to temperature, and then printing a sample file

which gently exercises the machine in the full extents of the X-Y plane, and prints enough material to clear out the head.

- In the office environment, dust can accumulate on the exposed feed-stock, and get incorporated into the plastic when melted in the extruder head. To mitigate this, the feedstock can be routed through a folded sponge or wiper mounted to the frame of the machine.
- When not in use, the machine should be protected by a dust-cover to reduce dust buildup and contamination on the feedstock and on the exposed drive motors, belts, and lubricated screws.

### 6.6. Notes on print modes

Various print quality levels were employed on the TAZ5 throughout the course of this investigation. Despite the obvious quality difference in terms of layer resolution, other important phenomena were observed. Fast mode prints thick layers, enabled by a rapid extrusion rate and high head velocity. This results in audible stress on the machine, as pops and clicks can be heard during the print operation that are not observed during the same prints on other quality settings. Additionally, the fast extrusion rate may result in lower filament temperatures, which may reduce bond strength to the lower layers. However, the thick extrusion of fast mode, coupled with the lower filament temperature and fast head movement results in much better unsupported bridging capability, allowing some parts to be built with no support material underneath overhanging sections.

## 7. OPERATIONAL SAFETY CONSIDERATIONS

The diversity of Additive Manufacturing and 3D printing technologies results in a range of system-specific safety concerns. During this investigation, several safety concerns were noted and managed with due care by following the operational safety warnings in the user manuals. Operator-managed hazards encountered in this project and identified in the Lulzbot TAZ5 user manual include Electric Shock Hazard, Burn Hazard, Fire Hazard, Pinch Hazard, Static Charge, and (operator) Age Warning. The following safety notes are relevant to both the TAZ5 and Dimension SST 1200es systems utilized in this project.

- Odor: Printing with different materials resulted in various levels of odor in the immediate vicinity of the machines. All print operations highlighted the need for appropriate environmental conditioning and ventilation in print areas. The systems utilized in this project are intended for indoor office / desktop use. As such, care must be applied when placing these systems in appropriate indoor locations.

- Heat: The Fused Deposition Model systems utilized in this investigation are thermal processes that employ high temperatures to melt linear plastic feedstocks. The TAZ5

print head operates at up to 300 degrees Celsius, and print surface operates at up to 110 degrees Celsius.  As an open-carriage design, the TAZ5 head and print surface are open to the air, and are unguarded.  The Dimension 1200 is an enclosed volume and print operations are suspended when the build-space access door is opened.  Inadvertent contact with the high temperature print head is significantly less likely with the Dimension 1200 than with the TAZ5.  The heat produced by these systems poses both a burn hazard to personnel, and a fire hazard to flammable materials or vapors in the vicinity of the machine.

- Electricity: Printers are electrical appliances with various cords and connectors, resulting in a potential risk of electric shock.  The Dimension 1200 and TAZ5 are office systems that operate on 110V wall power.  As an enclosed system, the Dimension 1200 has a single power cord exiting the cabinet.  As an open system, the TAZ5 has several power and control cables that are open to contact.  Placement of the machine is important to avoid trip hazards with power cords.

- Moving machinery: FDM machines operate by moving a print head, in space, over a build volume, which results in moving equipment and the associated pinch hazards.  As an enclosed system with a latched/sensed door to the build volume, the Dimension 1200 presents little risk of pinching operators.  The TAZ5 presents an open build volume with no intrusion sensors, and presents significant risk of pinching.

Other, industrial AM and 3D printing systems utilize high-energy lasers, finely powdered material feedstock, and toxic or caustic chemicals to dissolve support materials or finish models.  Each hazard presents associated risks; it is critical that system operators follow safety procedures in OEM manuals, and that facilities that house these capabilities are appropriately equipped for such systems.

All hazards were appropriately managed by system operators during the course of this investigation.  System operators should always follow appropriate operational safety warnings and cautions in OEM manuals and practice due care while working with such systems.


## 8.  FILE HANDLING FOR AM VS TRADITIONAL MANUFACTURING

Industry standards are well developed for commissioning a part via a traditional manufacturing process.  Typically, a material is specified, and a drawing with appropriate dimensions and tolerances is sent to a qualified fabrication shop.  It is then up to the shop to determine which equipment and processes to use to fabricate the desired part.  With the proliferation of inexpensive 3D printers, this model may no longer apply to distributed additive manufacturing.  Through the course of this investigation, it became apparent that there are a wide variety of ways to print any given part.  Variations such as orientation, infill density and geometry, layer thickness, extrusion temperature, etc. will all affect the final output. As such, additional

information beyond basic geometric dimensions and tolerances will be required in order to produce parts with the desired mechanical characteristics. In this way, 3D printing parts is more akin to composite manufacturing, in which parameters such as fiber orientation, layup order, resin infusion method, and curing temperature and duration are precisely controlled. For additive manufacturing processes, this is similarly complicated in that each additive manufacturing method requires a different set of machine parameters (e.g. print head temperature applies to FDM processes but not binder-jet processes).  A "complete" part order would contain an associated data file with manufacturing information to ensure that the produced part matches the original design. Such a file may contain:

- The 3D model file
- Material type(s)
- Color(s)
- Finish(es)
- Printing process(es)
- Build parameters
    - Part orientation
    - Layer thickness
    - Base and Shell thickness
    - Infill percentage
    - Infill pattern

# 9.  DESIRED CAPABILITY ENHANCEMENTS
Throughout the course of this investigation, observations and notes were made on desired additive manufacturing capabilities, which would be useful at both the individual level, or integrated into a single package.  These capabilities may exist in industry, however a cursory search has not revealed such products.

## 9.1. Additive Manufacturing Hardware Wish List
- Multi-axis FDM machine capable of complex layups: An FDM system with a 4th and 5th axis would enable the printing of significantly stronger parts, by reducing the potential for layer planes to be aligned with high-stress areas of a component. Such a system would be very similar to automated filament layup equipment used in the composites manufacturing industry.

- Travel mode: One feature of desktop 3D printer systems is their portability, however movement typically requires some level of disassembly and re-packaging of the machine to ensure safe transportation. A few simple features would significantly enhance the

portability of a desktop 3D printer, including locks for all movement axes, integrated/attached wiring and ancillary components, quick disconnects for any cabling, a balanced carry handle (or handles), tie-down points, and robust shock-isolating feet.

### 9.2. Additive Manufacturing Software Wish List

- Variable density infill: All of the slicing software packages utilized in this investigation are capable of generating a variety of infill patterns, however they are all of constant dimension. It would be valuable from a strength, weight, and cost perspective to have the capability to generate a variable density infill pattern with large voids in the center of a part, shrinking to smaller voids near the part walls.

- Variable quality: All of the slicing software packages utilized in this investigation are capable of coding parts for "fast", "normal", and "fine" quality, or some variation thereof, however the entire part is produced at this single quality setting. It would be valuable from both a time and part quality perspective to have the capability to code parts with variable print quality in which highly detailed sections would be printed in high quality, and low-detail sections would be printed "fast."

- Time-limited mode: All of the slicing software packages utilized in this investigation are quality-driven. It would be valuable to have the option to constrain a build to a certain time requirement, and have the software calculate the highest quality part that could be made within the time constraints.

# 10. ECONOMIC ANALYSIS

A cursory economic analysis was conducted as part of this investigation using known costs for printing operations on the TAZ5. As basic costs are known for materials (~$25/kg), power (~$0.22/kWh), and equipment recapitalization (~$100/200hrs), a simple non-labor cost per part can computed. Slicing software calculates the mass of material consumed. Power consumption was measured with a simple plug-in power meter (Kill-A-Watt P3). Print-time was measured with a timer. Costs for most print jobs were calculated and are included in the Appendix A print log, on prints for which the appropriate data was captured. Non-labor costs range from $0.35 (small Rocktopus) to $13.50 (large Vanderbilt mansion) per part. Non-labor production costs equalized fairly well across all print jobs to $0.07 per gram on the TAZ5, which can be used as a rough estimating tool for future prints. Labor for each print job is simple to estimate as well. It takes approximately 15 minutes to execute a print job, including approximately 10 minutes of set-up and warm-up time, and 5 minutes of shutdown time. Initial prints and complex prints require periodic monitoring on approximate 30 minute intervals to ensure that the print has not failed early on in the print job. Some printers have the ability to recognize print failure, and automatically halt a failed print job. Deburring time is the most variable, and can range from minutes to hours, depending on the complexity of the part.

# 11. OPPORTUNITIES FOR FURTHER INVESTIGATION

This investigation focused on the digital workflow of getting a 3D model transferred, translated, manipulated, and printed as an additively manufactured part. As such, several areas were left for potential follow-on investigation. Many of the following investigations have likely been performed already by industry or academia, and a literature search at minimum would be worthwhile to inform future Navy Additive Manufacturing efforts.

## 11.1.　Physical properties

- Quantitative part analysis: None of the parts produced during this investigation were analyzed for geometric dimensions and tolerances, part-to-part consistency, or strength. A follow-on investigation of such physical characteristics would be required prior to any use for the production of actual engineering parts.

- Exotic material capabilities: With the proliferation of inexpensive desktop FMD printers, a variety of advanced print materials have come to market. This includes materials that are translucent, magnetic, flexible, wood-like or stone-like, glow in the dark, etc.

- Multi-head printing: Many FDM machines (including the TAZ5) are dual-head capable, allowing for the simultaneous printing of two materials. This typically takes the form of primary and secondary support material, however also enables unique configurations involving rigid and flexible materials within the same part. This enables the capability to print rigid components with flexible links (e.g. treads, flex-shafting), rigid components with flexible surfaces (e.g. wheels/tires), and flexible components with rigid mounting points (e.g. rag-joints).

- Print parameter optimization: To ensure the best possible print quality, various settings such as nozzle temperature, retraction distance, layer thickness, nozzle speed, and others must be optimized. These settings will depend on the printed material as well as the individual printer. Optimal print settings should be determined prior to executing any print jobs for engineering parts (vs. models), which will be used in equipment.

## 11.2.　Model information and security

- Feasibility study of embedded "known-good" print parameters in .x3d: Even with familiar materials and machine settings, it can take several attempts to print an optimized version of a new part. On most model exchanges, the individual posting the part can add notes which may include print settings. An additional feature that is implemented on various model exchanges and libraries is an "I Printed This" link, where users can upload images, information, and lessons learned from actual print attempts. However, a fully detailed set of "known-good" print settings is rarely if ever included or referenced for most models. It would be beneficial to investigate the feasibility of embedding "known-good" print parameters into the 3D model itself.  This may be a

complicated proposition due to the variety of 3D printer types, however it would significantly increase the likelihood of successful print jobs.

- End-to-end file security:  In instances where actual parts and components are being printed, it is essential to ensure model integrity through the digital workflow. Model files could be compromised to introduce specific flaws resulting in reduced lifespan or critical failure modes. Simple, standard concepts such as a file checksum or hash sum should be built into any model library to provide a tool to validate the received model against the original file.

## 11.3.      Process analysis

- 3D printing and testing actual components for equipment and facilities: Once the dimensional accuracy and material strength properties of printed parts have been determined, it would be hugely informative to print certain non-critical replacement parts for equipment or facilities. Such an investigation would inform the process of requesting a print, obtaining a model, optimizing the print, and installing the component, as well as determine the practical utility of the printed piece, and user perceptions of interacting with the part. For example: how would users perceive and interact with a 3D printed door handle? Would they notice? Would they use the door differently?

- 3D scan to print - price point vs capability analysis: The proliferation of inexpensive desktop 3D printers has brought along a wide variety of supporting technologies, including 3D scanning. The capability to 3D-scan an object, generate and manipulate a model, and then print the model is now available at a variety of price points. At the low price-point, a user could employ a free stereophotgrammetric scanning application, free modeling tools, and print on a sub-$500 printer, while at the high end, a user could employ a $100k laser scanner, $50k industrial grade CAD package, and print on $1M metal sintering machine. Options exist at all price points in-between, offering different levels of capability. While the appropriate equipment depends on the specific application and requirements of the part, a general investigation of capabilities vs. price-point for the end-to-end process could beneficially inform future investments in tools and equipment for Navy end-users.

# 12. CONCLUSIONS

Additive Manufacturing is a rapidly evolving field, with diverse applications, which will change the field of manufacturing as we know it. It will allow for the rapid production of items ranging from models to full-strength parts, offering the ability to rebuild one-off legacy components, while simultaneously enabling the creation of previously un-producible items. Through this investigation of workflow from digital model to printed part, we have validated the potential to

produce usable, relatively inexpensive models and parts, with readily available low-cost tools. There are multiple paths from model to part, with a multitude of file formats and software options at every step. There are also a wide variety of printing processes and materials available to suit any application. The variety of file formats, programs, tools, and materials allow for multiple points to influence the end product at every step of the process. This provides tremendous opportunity for product customization; however it also provides myriad opportunities to "get it wrong." Though 3D printing is a new field, as with any production process, an experienced operator is critical to ensuring the output of a quality product that meets user requirements and expectations.

## 13. RECOMMENDATIONS

Due to the relative infancy of Additive Manufacturing as a field, there are numerous and varied opportunities for follow-on investigation as outlined in section 10.  An overarching development that would facilitate these investigations is the creation of a Navy digital model exchange library similar to the National Institute of Health model exchange (http://3dprint.nih.gov).  Such a model exchange would serve as collaborative hub for users in Government, Industry, and Academia (with the right partnering agreements and access rights) to investigate both physical and cyber-security aspects of AM, and would serve as a working reference library for future AM applications.  Additionally, it would be beneficial to investigate the feasibility of embedding printable model files in existing virtual environments (such as SPIDERS 3D) and Product Lifecycle Management databases (such as Autodesk Vault and ePLM IDE) currently used by the Navy.

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**APPENDIX A**

**RC3DP PRINT LOG**

| Print ID | Date | File | Material | Color | Length (m) | Mass (g) | Energy (kWh) | Projected Time | Actual Time | Fractional Hours | Material Cost | Energy Cost | Recapitalization Cost | Total Cost | Fill Fraction (%) | Shell Thickness (mm) | Bottom Layer (mm) | Layer Height (mm) | Head Temp (°C) | Bed Temp (°C) | Result | Model Software | Slicing Software | Settings | Quality | Support | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TAZ5-0001 | 9/28/2015 | Rocktopus | PLA | Black | | | | | | 0.00 | | | | | 20 | | | 0.25 | | | Success | | Cura | Basic | Normal | | >Succesful first print! |
| TAZ5-0002 | 9/29/2015 | Pier 1 (0.75x) | PLA | Black | 6.92 | 55 | | 3:23 | | 0.00 | | | | | 20 | 1 | 1 | 0.25 | 205 | 60 | Success | AutoCAD 2010 | Cura | Basic | Normal | Yes | >A support layer was printed under entire deck due to perimeter curb. The support was difficult to remove due to the large connected surface area, and it ripped the curb off with it in areas. >The bottom of the part required extensive de-burring due to tiny fibers of material left during nozzle transition over unsupported space. >The machine is incapable or resolving the narrow edges of the "sockets" left behind in place of pilings. Though the machine may have the global accuracy in the x-y plane, the feature resolution is limited by the extrusion nozzle diameter. >The pilings are extrememly fragile and are easily broken off of the pier structure. |
| TAZ5-0003 | 9/30/2015 | Pier 2 (0.75x) | PLA | Black | 5.29 | 42 | | 2:34 | | 0.00 | | | | | 20 | 0.5 | 1 | 0.25 | 205 | 60 | Success | AutoCAD 2010 | Cura | Expert | Normal | No | >The flat pier deck, laid down directly on the build plate, resulted in a faster print with a much better surface finish. >The piling holes were removed from the pier deck beams, which accelerated build time, and resulted in a much cleaner bottom surface. >Support features (feet) were added to the bottom of the model to minimize the breakage of the small pilings. >The same level of deburring was required to remove the nozzle flash (tiny hairs). |
| TAZ5-0004 | 10/5/2015 | Pier 3 (0.51x) | PLA | Black | 3.56 | 28 | | 1:48 | | 0.00 | | | | | 100 | NA | NA | 0.25 | 205 | 60 | Fail | AutoCAD 2010 | Cura | Expert | Normal | No | >The print failed on the first layer when the PLA feed broke at the input to the extruder head. This could have been due to cold temperatures in the office, a stress riser in the feed material, stress in the material based on the orientation of the stock roll, fatigue of the feedsock, or any combination of the above. |
| TAZ5-0005 | 10/5/2015 | Pier 3 (0.51x) | PLA | Black | 3.56 | 28 | | 1:48 | 2:59 | 2.98 | | | | | 100 | NA | NA | 0.25 | 205 | 60 | Success | AutoCAD 2010 | Cura | Expert | Normal | No | >Due to the maximum scale of the part, the "raft" material was printed off the edge of the build plate, however this did not affect the print job. |
| TAZ5-0006 | 10/5/2015 | Pier 1 (0.51x) | PLA | Black | 2.24 | 18 | | 1:10 | 1:57 | 1.95 | | | | | 100 | NA | NA | 0.25 | 205 | 60 | Success | AutoCAD 2010 | Cura | Expert | Normal | No | |
| TAZ5-0007 | 10/5/2015 | Pier 2 (0.51x) | PLA | Black | 2.19 | 17 | | 1:09 | 1:55 | 1.92 | | | | | 100 | NA | NA | 0.25 | 205 | 60 | Success | AutoCAD 2010 | Cura | Expert | Normal | No | |
| TAZ5-0008 | 10/6/2015 | Fire Extinguisher Bracket | PLA | Black | 1.54 | 12 | 0.39 | 1:21 | 2:36 | 2.60 | $ 0.30 | $ 0.09 | $ 1.30 | $ 1.69 | 20 | 1 | 1 | 0.25 | 205 | 60 | Success | AutoCAD 2010 | Cura | Expert | Normal | Yes | >The .stl file was scaled at 10x in cura to achieve a meaningful print size. >The orientation for this print was chosen to evaluate performance on tall and narrow support material, and holes or hollow spaces on Z-planes. >The support material as programmed worked very well underneath the overhanging sections, and to fill in the hollow features. >The resultant component was very weak and on mild handling, broke at a layer interface which appeared to exhibit incomplete bonding. >This component is very difficult to print, because there is projecting geometry along all axes. As a result, there are no obvious choices for the bottom face / base layer of the print. Any orientation will require support material to generate the desired geometry. > General Note: TAZ5 Power draw is 7-7.5W while idle, 130-150W while printing PLA |
| TAZ5-0009 | 10/8/2015 | Octopus | HIPS | Grey | | | 0.21 | | 0:38 | 0.63 | | | | | | | | 0.25 | 240 | 110 | Success | | Cura | Expert | Normal | No | >This print was executed to purge the nozzle of the prior PLA material. >A Kill-a-Watt P3 was connected in-line to monitor the energy usage of the machine. While printing HIPS with the associated nozzle and bed temps, the machine consumes ~350W while warming up and ~240W while printing. |
| TAZ5-0010 | 10/9/2015 | Pier 1 (0.60x) | HIPS | Grey | 3.65 | 29 | 0.50 | 1:44 | 1:55 | 1.92 | $ 0.73 | $ 0.11 | $ 0.96 | $ 1.79 | 100 | NA | NA | 0.25 | 240 | 110 | Success | AutoCAD 2010 | Cura | Expert | Normal | No | >Resultant print quality with HIPS is outstanding, to the point that no deburring at all is required of the part. There is no flash, no hairs to trim, etc. >Some of the vertical surfaces in the model did not print as vertical, but as sloped (i.e. the end of the pier). >HIPS exhibits larger thermal deformation than PLA. The pier section warped and bowed as the deck surface that was maintained at high temp against the heated build plate, contracted on removal and cooling. We will attempt to correct this bow by weighting/flattening and baking the model in an oven, and then controlling the cool-down rate to mitigate warping. Another potential way to mitigate this problem would be to build a slight pre-stess (negative bow) into the part geometry so that on cooling it would bend itself straight. The issue with this approach is the challenge of printing a negatively bowed surface on a machine designed to produce flat layers. |
| TAZ5-0011 | 10/14/2015 | Pier 2 (0.60x) | HIPS | Grey | 3.56 | 28 | 0.39 | 1:42 | 1:47 | 1.78 | $ 0.70 | $ 0.09 | $ 0.89 | $ 1.68 | 100 | NA | NA | 0.25 | 240 | 110 | Success | AutoCAD 2010 | Cura | Expert | Normal | No | >This model was left to cool on the bed (i.e. no forced removal), however this did not address the problem, and the end part was still bowed. |
| TAZ5-0012 | 10/14/2015 | Pier 3 (0.60x) | HIPS | Grey | 5.61 | 44 | 0.56 | 2:35 | 2:18 | 2.30 | $ 1.10 | $ 0.12 | $ 1.15 | $ 2.37 | 100 | NA | NA | 0.25 | 240 | 110 | Success | AutoCAD 2010 | Cura | Expert | Normal | No | >This model was printed diagonally on the build plate in order to maximize the available print size. |
| TAZ5-0013 | 10/15/2015 | Pier 1 (0.60x) | HIPS | Grey | 3.65 | 29 | | 1:44 | | 0.00 | | | | | 100 | NA | NA | 0.25 | 240 | 60 | Fail | AutoCAD 2010 | Cura | Expert | Normal | No | >This print was an attempt to minimize residual thermal stresses and reduce post production warping. >The base layer suffered an early bed-adhesion failure, resulting in print fail. |
| TAZ5-0014 | 10/15/2015 | Pier 1 (0.60x) | HIPS | Grey | 3.65 | 29 | | 1:44 | | 0.00 | | | | | 100 | NA | NA | 0.25 | 240 | 80 | Fail | AutoCAD 2010 | Cura | Expert | Normal | No | >This print was an attempt to minimize residual thermal stresses and reduce post production warping. >The base layer suffered an early bed-adhesion failure, resulting in print fail. |
| TAZ5-0015 | 10/19/2015 | uBoat | HIPS | Grey | 2.29 | 18 | 0.51 | 3:15 | 1:54 | 1.90 | $ 0.45 | $ 0.11 | $ 0.95 | $ 1.51 | | | | 0.25 | 240 | 110 | Fail | Sketchup | Cura | Expert | Normal | Yes | >This was an attempt to print a model of a uBoat sourced from the Sketchup 3D warehouse online model library. >The file format was .obj, and was a surface model with open voids. >The file was sucessfully imported into Cura, however the g-code layer preview indicated that there may be problems with missing layers. >This was confirmed during the print, as entire layers of the model were missing, and the printer attempted at times to print over no support material. >This worked with a very limited z-offset, however one of the missing layer sections was too large to print over unsuported. |
| TAZ5-0016 | 10/20/2015 | 07 INLS Shadowbox | HIPS | Grey | 3.67 | 29 | 0.35 | 1:11 | 1:24 | 1.40 | $ 0.73 | $ 0.08 | $ 0.70 | $ 1.50 | 10 | 0.5 | 1 | 0.25 | 240 | 110 | Success | Autodesk 123D Design | Cura | Expert | Normal | No | >This was a print of a small shadowbox to represent a program achievement. |
| TAZ5-0017 | 10/21/2015 | 1x INLS Shadowbox 60mm | HIPS | Grey | 1.32 | 11 | 0.20 | 0:25 | | | | | | | 10 | 1 | 0.45 | 0.25 | 240 | 110 | Success | Autodesk 123D Design | Cura | Expert | Normal | No | >Print of a smaller shadowbox with revised internal features. >Missing time data due to unattended run of print job. |
| TAZ5-0018 | 10/21/2015 | 16x INLS Shadowbox 60mm | HIPS | Grey | 21.10 | 167 | 1.78 | 6:57 | 8:11 | 8.18 | $ 4.18 | $ 0.39 | $ 4.09 | $ 8.66 | 10 | 1 | 0.45 | 0.25 | 240 | 110 | Success | Autodesk 123D Design | Cura | Expert | Normal | No | >This was the first attempt of a batch print job, with 16 copies of the same model simultaneously on the build plate in a 4x4 array. >The perimeter raft line was printed around the entire batch, not each individual model. >The machine would print a full layer of each model before moving onto the next model (i.e. there was no jumping back and forth between models). >The resulting parts were fairly consistant, with the main variation being in small areas of liftoff on the bottom surface. >All models exhibited some degree of adhesion failure at the corners, potentially revealing uneven heating of the build plate, or revealing a limitation with regards to long wait times between build layers. |
| TAZ5-0019 | 12/11/2015 | PierEnds (0.60x) | HIPS | Grey | 7.21 | 57 | | 3:24 | 3:58 | 3.97 | | | | | 100 | NA | NA | 0.25 | 240 | 110 | Success | AutoCAD 2010 | Cura | Expert | Normal | No | >Simultaneous print of Pier 1b and Pier 2a (the end sections) |
| TAZ5-0020 | 12/11/2015 | Pier 3 (0.60x) | HIPS | Grey | 5.65 | 45 | | 2:36 | 2:42 | 2.70 | | | | | 100 | NA | NA | 0.25 | 240 | 110 | Success | AutoCAD 2010 | Cura | Expert | Normal | No | |
| TAZ5-0021 | 12/12/2015 | Ohio sub 335mm | HIPS | Grey | 4.28 | 34 | 0.56 | 1:58 | 2:33 | 2.55 | $ 0.85 | $ 0.12 | $ 1.28 | $ 2.25 | 20 | 1 | 0.8 | 0.25 | 240 | 110 | Success | Sketchup | Cura | Expert | Normal | Yes | >Took printer home, leveled bed on setup in garage >Ambient temperature while printing was very low overnight at ~48 degrees F >Model was submerged 19mm into bed (in cura) >Model printed well, but warped on completion despite greater z-thickness |
| TAZ5-0022 | 12/13/2015 | LPD17 | HIPS | Grey | 4.96 | 39 | 0.73 | 2:13 | | 0.00 | | | | | 20 | 1 | 0.8 | 0.25 | 240 | 110 | Success | | // | Cura | Expert | Normal | Yes | |
| TAZ5-0023 | 12/14/2015 | Cleat | HIPS | Grey | 2.08 | 16 | 0.37 | 0:57 | | 0.00 | | | | | 15 | 1 | 0.8 | 0.25 | 240 | 110 | Success | | | Cura | Expert | Normal | Yes | |
| TAZ5-0024 | 12/14/2015 | FE Bracket Meshmizer | HIPS | Grey | | | | | | 0.00 | | | | | | | | | | | Fail | | Meshmixer | | | | >gcode generated in Meshmixer >Strange branching organic shapes generated as support material >Part fail when nozzle tipped over one of the support structures |
| TAZ5-0025 | 12/14/2015 | LPD17 | HIPS | Grey | 4.96 | 39 | 0.76 | | 3:18 | 3.30 | $ 0.98 | $ 0.17 | $ 1.65 | $ 2.79 | 20 | 1 | 0.8 | 0.25 | 240 | 110 | Success | | // | Cura | Expert | Normal | Yes | |
| TAZ5-0026 | 12/15/2015 | LPD17 Big | HIPS | Grey | 20.07 | 159 | 3.51 | 14:14 | 15:56 | 15.93 | $ 3.98 | $ 0.77 | $ 7.97 | $ 12.71 | | 1 | 0.8 | 0.18 | 240 | 110 | Success | | // | Cura | Expert | High | Yes | >Note that the larger model has some strange artifacts near/above support material. >Botom delamination (Front bow, and rear corners) as well as thermal stress warping. Both phenomenon are in opposing directions, making the bottom sine-shaped. |
| Strat-0001 | 12/11/2015 | Fire Extinguisher Bracket | ABS | Gray | | | 6.35 | | 14:07 | 14.12 | $ - | $ 1.40 | $ 7.06 | $ 8.46 | | | | | | | | | Catalyst 4.3 | | | | >Came out well, support material broke off easily. Spt material looks organic like tree branches. |
| TAZ5-0027 | 12/21/2015 | Vanderbuilt Mansion 200mm HIPS | HIPS | Grey | 37.31 | 295 | 2.22 | 8:54 | 11:18 | 11.30 | $ 7.38 | $ 0.49 | $ 5.65 | $ 13.51 | 10 | 1 | 0.8 | | | | | | | | Fast | No | >Machine is audibly stressed when printing on fast mode. There are more frequent pops and clicks from the print head. >Fast print, with high nozzle speed and fast extrusion allows for extended bridging and printing without support in certain geometries. >Layer adhesion may be compromised based on filament temperature. Several cracks between layers emerged on one side of the model during the print. |
| TAZ5-0028 | 12/22/2015 | Rocktopus 2hand ABS 60mm | ABS | Black | 0.52 | 4 | 0.13 | 0:21 | 0:26 | 0.43 | $ 0.10 | $ 0.03 | $ 0.22 | $ 0.35 | 20 | 1 | 0.8 | 0.25 | 240 | 110 | Success | | NR | Cura | Basic | Normal | No | |
| TAZ5-0029 | 12/22/2015 | Vanderbuilt ABS 100mm 10 fill | ABS | Black | 7.95 | 63 | 1.16 | 5:05 | 5:08 | 5.13 | $ 1.58 | $ 0.26 | $ 2.57 | $ 4.40 | 10 | 1 | 0.36 | 0.18 | 240 | 110 | Success | | // | Cura | Expert | High | No | >Some of the finer features such as the window mutins did not render, though at first glance, they should have been within the resolution of the printer. >Cura may have a minimum feature size, below which it does not render a print. |
| TAZ5-0030 | 12/23/2015 | Pipe Cap | ABS | Black | 3.17 | 25 | 0.51 | 1:46 | 2:19 | 2.32 | $ 0.63 | $ 0.11 | $ 1.16 | $ 1.90 | 100 | NA | NA | 0.18 | 240 | 110 | Success | 123D Design | Cura | Expert | High | Yes | >STEP file downloaded from McMaster.com, translated to .stl in 123D design, and sliced in Cura |
| TAZ5-0031 | 1/22/2016 | 16x Rocktopus HIPS 60mm | HIPS | Grey | 7.75 | 61 | 0.88 | 2:49 | 3:44 | 3.73 | $ 1.53 | $ 0.19 | $ 1.87 | $ 3.59 | 20 | 1 | 0.8 | 0.38 | 240 | 110 | Success | | // | Cura | Basic | Fast | No | >Each octopus appears to be unique based on the start and stop points at each layer. |
| TAZ5-0032 | 1/15/2016 | 16x Rocktopus HIPS 60mm | HIPS | Grey | 7.75 | 61 | 0.88 | 2:49 | 3:44 | 3.73 | $ 1.53 | $ 0.19 | $ 1.87 | $ 3.59 | 20 | 1 | 0.8 | 0.38 | 240 | 110 | Success | | // | Cura | Basic | Fast | No | |
| TAZ5-0033 | 1/25/2016 | 16x Rocktopus HIPS 60mm | HIPS | Grey | 7.75 | 61 | 0.88 | 2:49 | 3:44 | 3.73 | $ 1.53 | $ 0.19 | $ 1.87 | $ 3.59 | 20 | 1 | 0.8 | 0.38 | 240 | 110 | Success | | // | Cura | Basic | Fast | No | |
| TAZ5-0034 | 2/2/2016 | Rocktopus 2hand ABS 60mm | HIPS | Grey | 0.53 | 4 | | 0:15 | | | | | | | 20 | 1 | 0.8 | 0.38 | 240 | 110 | Success | | // | Cura | Basic | Fast | No | |